ENGINEERING DATA COMPENDIUM

Human Perception and Performance

VOLUME III

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ENGINEERING DATA COMPENDIUM

Human Perception and Performance

VOLUME III

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Integrated Perceptual Information for Designers Program

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"Engineers have been aware of the desirability of designing equipment to meet the requirements of the human operator, but in most cases have lacked the scientific data necessary for accomplishing this aim."

In honored memory of

PAUL M. FITTS

We dedicate this work to the past and future achievements
of the organization he founded

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Contents for Volume III

Foreword

As a result of his experience in the United States Army Air Force during World War II, Dr. Paul M. Fitts fully comprehended the need for the translation of human engineering design criteria and data into a form readily accessible to the design team. He appreciated the complexity of the typical crew interface design problem, in terms of the multiple technologies involved, the interdisciplinary skills required of the design team, and the many compromises necessary to achieve a practical solution to a complex design issue. This belief in the value of concise, reliable human performance data for practical application by designers was reflected in his approach to applied problems throughout his professional career. This concern for enhancing the value of basic technology to aid the solution of practical problems has continued to influence the organization responsible for the development of this *Engineering Data Compendium* and thus it represents an extension of Paul Fitts' conviction that a well-designed crew interface significantly contributes to the safety and effectiveness of the system in which it is incorporated.

This *Engineering Data Compendium* is the second in a series of tools aimed at providing the data necessary for the human engineering design of crew systems. The first was the two-volume *Handbook of Perception and Human Performance*, edited by K. Boff, L. Kaufman, and J. Thomas and published by John Wiley and Sons, New York, in 1986. The Handbook contains an extensive treatment of the basic data on perception and performance designed for use by the human engineering specialist. It can be considered the primary reference for the Compendium.

Although necessarily limited in scope, e.g., physical anthropology is not treated, the Compendium provides in-depth treatment of human perception and performance in terms of the variables that influence the human operator's ability to acquire and process information, and make effective decisions. Both subject matter experts and potential users were consulted on an unprecedented scale in the course of preparation and review of these volumes and every effort was made to ensure the practical value of the data presented. To meet this objective, the guidance and support of a variety of US federal agencies concerned with fielding complex systems were obtained throughout the development and testing of the Compendium. Potential users were consulted on all aspects of Compendium development, including content, readability and packaging. These consultations and extensive field testing are responsible for the usability of the volumes in typical design settings. For instance, the presentation anticipates a user who, while reasonably sophisticated in the application of technical and quantitative data, may have little prior training or experience with a specific technical area of immediate interest. For this reason, details regarding statistical and methodological reliability are included. In all entries, data are presented in an easy-to-use, standardized format and re-scaled to Système International (SI) units wherever appropriate. The packaging of the individual volumes, including the binders, volume size, internal organization, composition and type design, is based on field test results and agency guidance. Careful attention was paid to data accessibility in the design of the Compendium. Data may be accessed through a detailed table of contents, as well as key word indices, glossaries, checklists keyed to specific design topics, and knowledge maps logically organized to reflect the hierarchy of topics treated.

The *Engineering Data Compendium* is packaged in four volumes — three loose-leaf volumes containing design data and a bound *User's Guide*. It is anticipated that within a given organizational element, the three data volumes can be centrally maintained, with the *User's Guide* more generally available. The three data volumes in the loose-leaf format can thus be dynamic in the sense that multiple users can share the common data base they represent.

It was the intention of the editors and the Human Engineering Division of the Armstrong Aerospace Medical Research Laboratory to produce a practical compendium of human engineering guidance in the tradition of Dr. Paul M. Fitts. These volumes are offered to the design community at large for their evaluation of our success in meeting this objective.

CHARLES BATES, JR.
Director, Human Engineering Division

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Preface and Acknowledgments

Attempting to use the research literature in perception and human performance as a means for guiding tradeoffs between equipment characteristics and human performance capabilities or limitations can be a formidable task. This is due, in part, to difficulties in retrieving and interpreting specialized data from the multitude of information sources distributed widely over a variety of report media. The intent of the *Engineering Data Compendium* is to provide an alternative basis for efficient access to the research literature. It is designed as a professional desk reference for the practitioner in search of pertinent and reliable information on human perception and performance.

The worth of any secondary reference is inextricably tied to the user's trust in the author's objectivity and expertise in selecting and interpreting the subject matter. In the design and development of the Compendium, we have made a deliberate commitment to honor this trust.

The *Engineering Data Compendium* owes its existence to the efforts, committment and faith of an extraordinary group of individuals—extraordinary in terms of their skills, dedication, professionalism, endurance, and sheer numbers. Below, we provide an outline of the development of the Compendium so that acknowledgments to contributors may be placed within the relevant context.

Development of the Compendium

The development of the *Engineering Data Compendium* involved many iterative stages, procedures, and processes requiring control and communications on an international scale among many participants and organizations in government, industry, and academia. In addition to the formidable challenges in accessing and dealing with technical data, many hundreds of hours were spent in planning the logistics of the contracting, management and production of the Compendium. The principal stages in the development of the *Engineering Data Compendium* are briefly outlined below.

Data Consolidation

The first step in the development of the *Engineering Data Compendium* was to identify, collect, and consolidate human perception and performance data relevant to design requirements into a primary reference—the *Handbook of Perception and Human Performance*. To accomplish this task, the domains of sensation, perception, human information processing, and human performance were reviewed. Forty-five technical subareas were selected for detailed treatment on the basis of their potential value to control and information display design. A team of more than sixty recognized experts in these technical subareas was assembled to achieve this data consolidation. The Handbook was completed in December 1984 and published in two volumes by John Wiley and Sons in Spring 1986. It has served as the principle data resource in the development of this Compendium and is frequently cross-referenced as a source of useful background information and more detailed treatment of selected empirical and theoretical topics.

Data Selection and Evaluation

The selection and evaluation of data appropriate for the Engineering Data Compendium were accomplished through a series of structured reviews of selected data sources and the candidate items extracted from them. Specialists familiar with a given topic area first reviewed information on that topic contained in the primary data source (the Handbook or applied literature) and selected candidate data items for the Compendium. A brief proposal was prepared for each data item that specified the anticipated treatment in the final entry, including data functions, illustrations, and citations of original reference sources (journal articles, technical reports, etc.). This proposal was then evaluated by at least three reviewers with expert knowledge in the subject area. Candidate data items were assessed for applicability (generalizability and usefulness for system design), representativeness (soundness and currency of the data), and overall appropriateness for the Compendium. Reviewers were free to suggest alternative or supplementary data on the specific topic, recommend different organization or treatment, or reject the proposed data item altogether as inappropriate for the *Engineering Data Compendium*.

Entry Development

Candidate data items that passed this review were assigned to selected contributors who completed the necessary research and prepared draft entries in the required format. These drafts underwent an intensive editorial and technical audit that included recursive evaluations of each entry against the original candidate entry proposals as well as the data sources on which the entries were based. Special attention was given to ensuring that details of the methodology, data analysis, and experimental results were represented accurately in the entry (and that the errors occasionally found in the original reference sources were not reproduced in the Compendium). Many entries were rewritten, combined, or eliminated during this editing stage.

Edited entries were then sent for review to subject matter experts and, wherever possible, to system designers. The entries were evaluated along three dimensions:

(1) Relevance: Will the information be useful to the target groups, or is it of purely academic interest?

(2) Content: Is the basic information thoroughly represented? Is it accurate and usable as presented?

(3) Form and style: Does the entry adhere to the prescribed format? Is it written in clear and concise language?

During the course of the successive outside reviews that occurred as each data item progressed from entry proposal to final written entry, the qualifications and background of the reviewers selected shifted from expertise in the specific subject matter under review to experience with the conditions under which the information could be applied. This procedure assured that the information in the Compendium would not only be accurate and up to date but also relevant to system design needs and comprehensible to non-specialists in the field.

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Prototype

In 1984, a prototype version of the Compendium was produced, both to provide suitable materials for on-going field evaluations and to serve as an interim product in sustaining the enthusiasm of the project's patient sponsors at DoD and NASA.

The prototype Compendium was comprised of two technical sections dealing with stereoscopic vision and vibration and display perception. These topic areas were developed in full to demonstrate the flexibility of the format in covering various topics as well as different categories of information (e.g., data, models, tutorials). So that the prototype would fully embody the image and feel of the final product, we designed and incorporated front matter, keyword indices, glossaries, and other organizational and packaging elements. Compilation of the prototype served as a trial by fire for IPID project team members that allowed the refinement of managerial and editorial procedures to make production of the final volumes flow more smoothly.

Final Preparation

Final preparation of the entries for publication involved interactive audits, edits, reviews and much retyping across multiple drafts. Quality control concerns were central to our processing of the entry manuscripts. Quantitative formulations, authors' names, and reference citations were checked and rechecked. Several thousand figures, tables, and illustrations were drafted, converted to SI (Système International) units, reviewed, proofed and corrected. Permissions for the use of copyrighted materials were sought and paid for, and the multitude of individual credit lines specified by copyright holders were inserted.

Production

To maintain control over Compendium design, product quality, and costs to the final consumer, we assumed the traditional role of publisher in managing the production, manufacturing and distribution of the Compendium. This included the complete design of the document (artwork design, type style and layout of text, binder design), type composition, proofreading of galleys and page proofs, printing and photographic work, binder manufacture and packaging. In addition, we took primary responsibility for defining the logistics for the shipping, handling, warehousing and distribution of the Compendium.

Acknowledgment of the Cast

It is difficult, given a project of this scope, to acknowledge appropriately the contributions and dedication of the many individuals indispensable to its success. This task is further complicated by the many different roles assumed by contributors, including fiscal support, management, and administrative and secretarial support. All of these individuals deserve considerably greater recognition for their contributions than can possibly be achieved by this acknowledgment. Without doubt, we have inadvertently omitted some individuals who made contributions; for this, we sincerely apologize.

The program was accomplished under USAF project 7184, task 26, work units 02, 03 and 06. Crucial support was provided by Colonel Donald Carter in his role as Program Manager of the program element under which this Compendium was funded. It was managed through the offices of the Visual Display Systems Branch of the Fitts Human Engineering Division of the Armstrong Aerospace Medical Research Laboratory, Wright-Patterson Air Force Base, OH. Thomas A. Furness III, Branch Chief, and Charles Bates, Jr., Division Chief, provided encouragement and moral support during the many periods of frustration inevitable in a project of this size. Most importantly, they created an environment in which novel ideas, such as the one that inspired this project, could be nurtured and sustained through final delivery of products. As the Compendium took form, Charlie orchestrated the support and marshalled the resources needed for its production and widespread distribution throughout the international human engineering community.

In the branch and the Fitts Human Engineering Division, we are indebted to many individuals for support and constructive criticism that helped define the project's conceptual basis and immeasurably improved the quality of the product. Gloria Calhoun aided much of the early planning that enabled the project to flourish. Herschel Self contributed long hours and enormous intellectual effort in the review, editing and critiquing of Compendium entries. Herschel single-handedly drafted the thousands of design-related questions that comprise the design checklists in the *User's Guide* (Vol. IV). Robert Eggleston contributed many thoughtful suggestions and much personal energy in aiding major aspects of the project. David Post, our resident color perception expert, gave generously of his time and expertise to ensure the technical accuracy of the treatment of color vision in the Compendium. Professional contributions and peer reviews were also provided by Mark Cannon, Bill Crawford, Thomas Furness, Fran Green, Michael Haas, Steve Heckart, Gilbert Kuperman, Grant McMillan, Wayne Martin, Gary Reid, Donald Topmiller, Sharon Ward, Richard Warren, and Melvin Warrick. Al Chapin, Division Custodian, made heroic efforts to ensure that the special binder requirements for the Compendium would be met. Last, but by no means least, Barbara Osman, Executive Secretary for the Fitts Human Engineering Division, carefully proofread volumes of project correspondence. Sandy Stevenson expedited contractual matters and expertly proofread all IPID product reports. Within the Visual Display Systems Branch, Tanya Ellifritt personally gave wide-ranging administrative assistance and attention to the project.

We are also very grateful for the advocacy and support provided by Henning Von Gierke (Division Chief) and members of the technical staff of the Biodynamics and Bioengineering Division of the Armstrong Aerospace Medical Research Laboratory. These include the invaluable contributions by Tim Anderson, Jim Brinkley, Urena Erasmo, Charles Harris, Richard McKinley, Thomas Moore, Charles Nixon, Daniel Repperger, Richard Shoenberger, Mark Stephenson, Bill Welde, and Robert Van Patten.

Ken Zimmerman and Patricia Lewandowski, of the AAMRL Scientific and Technical Information Office, worked with the appropriate agency officials to clear many limited-distribution government documents for public release so that useful data from these reports could be included in the Compendium.

The idea for the project evolved from a former Air Force effort for which much inspiration is owed our colleagues Patricia Knoop, Lawrence Reed, Rick Gill, Bert Cream, Don Gum, and Gordon Eckstrand. Belief in the idea of an

Engineering Data Compendium and its potential value to the design engineering community spurred Art Doty, former Chief Engineer for the Air Force Deputy for Simulators, to agree to provide major sponsorship of this project. There is little doubt that this initial support opened the doors to subsequent multi-agency funding that supported the project and, in fact, enabled its survival. We are also grateful for the steadfast support and trust throughout the project provided by the Office of the Air Force Deputy for Training Systems (formally the Deputy for Simulators), presently under the leadership of Colonel Wayne Lobbestael. Many useful suggestions and valuable support were rendered by the technical and administrative staffs of the Training Systems SPO. In particular, we wish to acknowledge Jim Basinger, George Dickison, Jim O'Connell (current Chief Engineer), Bob Swab, Chris Hanson, and Nancy Droz.

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In addition to the Armstrong Aerospace Medical Research Laboratory and the Air Force Deputy for Training Systems, agencies within each of the Armed Services and the National Aeronautics and Space Administration (NASA) provided financial and technical support. The principal individuals involved in this vital support are: Walter Chambers and Dennis Wightman of the Naval Training Systems Center, Orlando, FL (NTSC); Stan Collyer, now with Naval Systems Command, who initiated Navy participation in the project; Charles Gainer, Chief of the Army Research Institute (ARI) Field Unit at Ft. Rucker, AL; Clarence Fry of the Army Human Engineering Laboratory, Aberdeen Proving Grounds, MD; Thomas Longridge, formerly with the Air Force Human Resources Laboratory, now with ARI, Ft. Rucker; Melvin Montemerlo, NASA Headquarters, Washington, D.C.; Walter Truskowski of NASA Goddard Space Flight Center, MD; and David Nagel of NASA Ames Research Center, CA.

Particularly worthy of acknowledgment is the outstanding demonstration of support and approval for our efforts by NATO's Advisory Group for Aerospace Research and Development (AGARD) and its Technical Director, Irving C. Statler. He readily supported the recommendation of Air Commodore G.K.M. Maat, Royal Netherlands Air Force, and Colonel K. Jessen, Royal Danish Air Force, Chairman and Vice Chairman, respectively, of the Aerospace Medical Panel of AGARD, to cost-share the manufacture of this Compendium to ensure its distribution throughout the NATO countries. For expediting NATO participation in the production of the Compendium, we are further indebted to George Hart, Technical Information Panel Executive, and Majors L.B. Crowell and John Winship, Canadian Forces, Aerospace Medical Panel Executives.

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Introduction

In science, by a fiction as remarkable as any to be found in law, what has once been published, even though it be in the Russian language, is spoken of as known, *and it is too often forgotten that the rediscovery in the library may be a more difficult and uncertain process than the first discovery in the laboratory.*

Lord Rayleigh (1884)

Despite spectacular advances in display systems and data handling technologies, modern crew systems confront their operators with a staggering volume of codified information that competes for scarce attentional and control resources. Unabated, these increasing psychological and physiological demands have the potential to undermine critical technology gains in system performance. While it is generally accepted that the ability of the human operator to acquire and process task-critical information is a key contributor to system effectiveness, significant difficulties arise in translating this realization into meaningful action in system design and acquisition. Recognition of the problem has spurred concerted efforts across the Department of Defense to influence early design tradeoffs in favor of an improved match between system specifications and operator characteristics.

Whether or not an optimal fit will be achieved between system capabilities and the perceptual and performance capabilities of the operator depends, among other things, on the nature of the design process, the inclinations and biases of designers, and the availability of usable data resources. In particular, human performance data are needed in a form and at a level of precision that will allow operator characteristics to be traded off against other design variables (Ref. 1).

While a good deal of potentially useful human performance data exist, these data have had very little direct impact on the design of system interfaces. In large measure, this failure to translate relevant research findings into practice is due to the perceived high costs and risks associated with their *accessibility, interpretability,* and *applicability* for system design problems.

Accessibility. Much of the research data of potential value to system designers is embedded in the huge volume of psychological and technical literature distributed among countless journals, periodicals, and government and industrial reports. Furthermore, the contextual and theoretical framework within which researchers typically generate and disseminate technical information does not necessarily coincide with the logical framework or needs of the practitioner. Designers may not readily locate the information they need in the places they expect to find it (Ref. 2).

Interpretability. The difficulty of the nonspecialist in understanding and evaluating the technical data found in traditional sources of ergonomics information is also a major problem. Researchers typically feel little responsibility to the applied world beyond reporting their findings in the scientific literature. Hence, interpreting scientific communications generally adds considerable overhead and in fact may be a barrier for the practitioner who lacks the ability to evaluate the relevance of ergonomics information to the problem at hand (Ref. 3). The human factors profession is particularly guilty of failing to tailor the presentation of human perception and performance data to the needs of practitioners (Ref. 4).

Applicability. A major problem influencing the use of ergonomics data is the obvious difficulty and continuing controversy regarding the relevance and translatability of research data to practice (Refs. 5, 6). Not only are data collected under highly controlled circumstances, but the experimental conditions set by researchers are often so synthetic that a major stretch of the imagination is required to find analogous circumstances in the real world to which these conditions might relate. The concern is that data collected under such highly limiting conditions cannot be reasonably extrapolated to multivariate environments where it is difficult to take account of the many interacting factors that may contribute to performance variability. Unfortunately, this criticism is also true of most applied multivariate studies in which the problems of comparing and extrapolating between experimental and dynamic "real world" contributors to variance are severely compounded. Therefore, if the utility of ergonomics is gauged solely in terms of the extent to which it can supply "cookbook" answers to designers, then the ergonomics discipline itself will be judged a failure. Neither the time nor the resources are ever likely to exist, particularly in the midst of design problem solving, to evaluate parametrically all the conditions pertaining in an interactive real-world system problem. Ergonomics data are useful not because they are directly translatable to multifactor conditions (though some "cookbook" answers exist for some "cookbook" questions), but rather because they offer cues, clues, and confirmations to support the designer's reasoning processes (Refs. 3, 7).

The *Engineering Data Compendium: Human Perception and Performance* produced under the Integrated Perceptual Information for Designers (IPID) project is intended to provide ergonomics data as a technical resource for system design. To help ensure that the *Engineering Data Compendium* finds its way to the designer's workbench, rather than simply to the designer's bookshelf, the presentation of information has been tailored to the needs of the user. In particular, during development of the Compendium, systematic attention has been given to: (a) defining and validating approaches to effectively communicating ergonomics data to system designers in terms of presentation format, style, terminology, and level of technical content; and (b) enhancing the accessibility of specific technical information relevant to design problems by providing the user with reliable means of locating specific data.

In the development of the *Engineering Data Compendium,* we have learned from previous efforts in this area (Refs. 8-12) and have freely borrowed and integrated their successful elements into our approach. Nevertheless, the Compendium does have several unique features: one is the range and depth of the perception and performance data treated; another is the approach devised for communicating this information so that it is both comprehensible and accessible to the intended user.

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What the Compendium Contains

The available body of psychological research contains a staggering volume of human perceptual and performance data and principles that are of potential value to system design. This includes data regarding basic sensory capacities and limitations (contrast sensitivity, spatial/temporal eye movement dynamics, aural and vestibular thresholds, etc.), as well as perception and human information processing (visual, aural, and proprioceptive pattern recognition, information portrayal, etc.). In the *Engineering Data Compendium,* basic data and principles from these areas are treated in depth and combined with applied human factors data into a single comprehensive reference source.

Eight classes of information are included in the *Engineering Data Compendium:*

1. ***Basic and parametric data*** (e.g., dynamic range of the visual system, spatial and temporal contrast sensitivity functions, physical response constants of the vestibular system, receiver operating characteristic curves).

2. ***Models and quantitative laws*** (e.g., CIE spaces, probability summation, operator control models). A model or law had to meet two criteria in order to be included: (a) it had to provide a way of interpolating or extrapolating existing data and relating them to a specific application, either to answer a design question directly or to specify the research needed to answer the question; and (b) it had to have a well defined and documented domain of reliable application.

3. ***Principles and nonquantitative or nonprecise formulations*** that express important characteristics of or trends in perception and performance (e.g., Gestalt grouping principles, interrelationship between size and distance judgments, depth and distance cues).

4. ***Phenomena*** that are inherently qualitative or that are general and pervasive, although quantitatively described in specific instances (e.g., simultaneous brightness contrast, visual illusions, motion aftereffects).

5. ***Summary tables*** consolidating data derived from a body of studies related to a certain aspect of sensation, perception, or performance (e.g., table showing different acuity limits as measured with Landolt rings, grating patterns, etc.; table summarizing the effects of various factors known to affect stereoacuity).

6. ***Background information*** necessary for understanding and interpreting data entries and models (such as rudimentary anatomy and physiology of sensory systems, specialized units of measurement or measurement techniques; specific examples are anatomy of the ear, geometry of retinal image disparity, colorimetry techniques).

7. ***Section introductions*** to topical areas that describe the topic and set out its scope, explain general methods used in the given area of study, note general constraints regarding the application of data in the area, and provide references for further general information.

8. ***Tutorials*** containing expository material on general topics such as psychophysical methods, linear systems analysis, signal detection theory, etc., included both to help the user fully understand and evaluate the material in the Compendium, and to support research and evaluation studies in engineering development.

To make pertinent information more accessible to the user, graphic modes of presentation are used wherever possible. The Compendium contains over 2000 figures and tables, including data graphs, models, schematics, demonstrations of perceptual phenomena, and descriptions of methods and techniques. Other features of the Compendium include indicators of data reliability, caveats to data application, and the use of standardized units of measurement (Système International).

Data Presentation

To help the user locate and interpret pertinent information, a standardized presentation format has been developed for entries in the *Engineering Data Compendium* that is tailored to the needs of the design engineer. This format has evolved over several years through an iterative process of review and discussion with the user community, sponsors, and consultants. In its present form, it represents our best attempt at "human factoring" the presentation of relevant perceptual and performance data.

The basic unit of information in the Compendium is the individual *entry* addressing a narrow, well-defined topic. Each entry is centered around a graphic presentation such as a data function, model, schematic, etc. Supporting text is compartmentalized into a set of text modules or elements. Each of these elements provides a concise subunit of information designed in content and style to support understanding and application of the data. The entry format is described in detail in the *User's Guide* (Vol. IV).

The prescribed entry format has the advantages of both formal structure and adaptive modularity. The appearance of entries is generally uniform. In most cases, entries are presented on two facing pages. The type of information contained in each entry subsection is consistent across entries. Hence, the user can confidently access those elements needed to interpret or apply the data without being distracted by information irrelevant to the problem at hand. The format is also adaptable; only those elements appropriate to a given class or type of entry are presented.

Data Access

The *Engineering Data Compendium* provides system designers with a wealth of relevant human performance and perceptual data heretofore unavailable to them in a useful form. However, access to the data in the Compendium is complicated by the fact that the perceptual concepts that underlie the data typically fall outside the scope of the training or experience of most practitioners. If these concepts are to be recognized as relevant to specific design problems, they must be linked to information or issues familiar to the designer.

Several different means of accessing material are provided so that users with different interests and technical background can readily locate the information pertinent to their needs.

1. ***Tables of contents.*** Two levels of contents listings are provided: A brief, global table of contents enabling the user to quickly determine the overall scope and organization of the Compendium may be found at the front of each volume. An expanded table of contents listing all subsections and entries by title is provided in the *User's Guide* (Vol. IV). An expanded contents for each major section of the Compendium is also located at the beginning of the corresponding section.

*2. **Sectional dividers.*** Each major section listed in the table of contents can be located rapidly by means of marginal tab dividers imprinted with the corresponding subject area title. Three of the topical sections (Sections 1.0, 5.0 and 7.0) are further subdivided by marginal tabs using size and color codings appropriate to the hierarchical scheme.

*3. **Glossary of technical terms.*** A brief glossary of definitions is provided at the beginning of each major topical section. A consolidated glossary is contained in the *User's Guide*.

*4. **Indices.*** A sectional keyword index is provided at the beginning of each major topical section. This index is designed to help both naive and experienced users formulate their search questions in terms of relevant perceptual issues that may then be directly accessed within the Compendium.

*5. **Logic diagrams.*** At the beginning of each major topical section is a diagram showing the taxonomic hierarchy of subtopics and supporting entries for that section.

*6. **Cross references.*** Each Compendium entry includes extensive cross references to other Compendium entries and to sections of the *Handbook of Perception and Human Performance* (Refs. 11, 12) that provide more detailed treatment of a topic or subtopic, discussion of related topics, or explanatory material to aid in understanding or interpreting the data.

*7. **Design checklists.*** Found in the *User's Guide* are checklists of design-oriented questions suggesting human performance variables that should be considered in the specification of equipment.

In addition, the *User's Guide* comprising Volume IV of the Compendium provides instructions for accessing data and a description of the format and organization of information in the Compendium.

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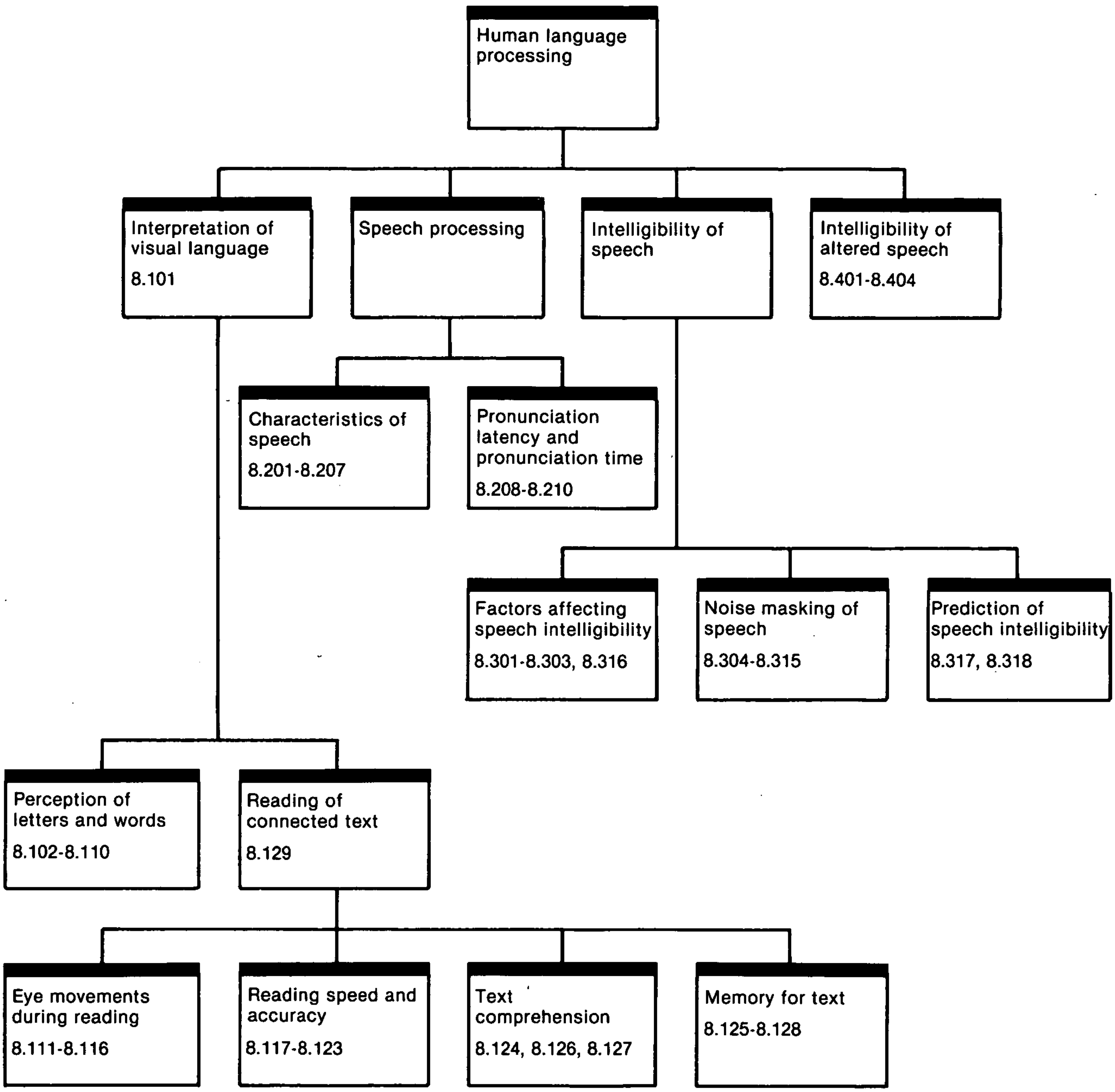
Organization of Entries



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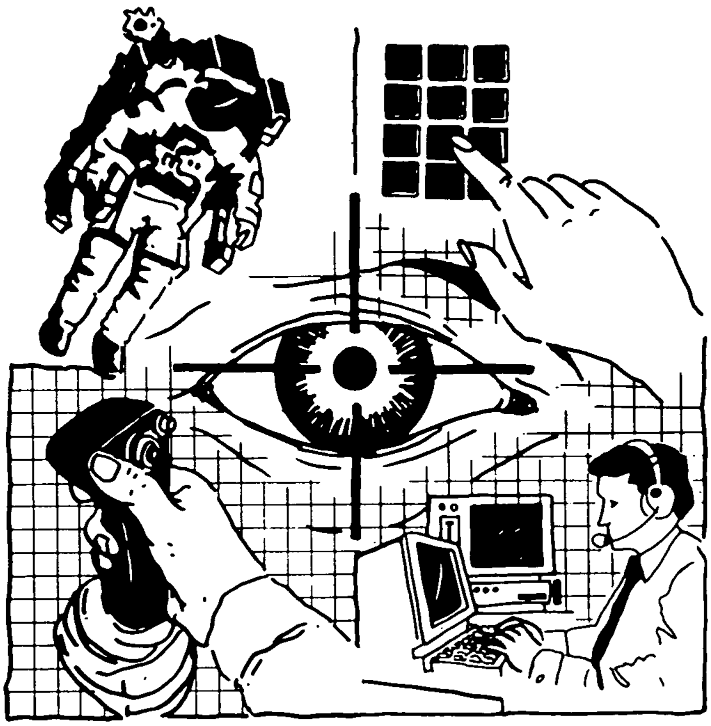
Section 8.4 Intelligibility of Altered Speech

Section 8.0 Human Language Processing



8.101 Perceiving Visual Language

Key Terms

Communications; eye movements; reading; text comprehension; text engineering; verbal memory; word recognition

General Description

Reading consists of the perception, comprehension, storage in memory, and subsequent use of information from visually presented language. It is an indispensable skill in modern societies. Many high-technology occupations and professions specifically involve the creation, recording, transmission, or analysis of lists, tables, text, or other forms of written language. People who interact with command, control, or communication systems must read the system's information to perform successfully. These system messages range from symbols on keys to words and phrases on display panels, to passages of connected discourse that provide instructions or information necessary to make decisions. Finally, the vast majority of modern occupations are learned, in part, through training programs that include large amounts of material to be read; certainly the educational enterprise as a whole relies heavily upon the acquisition of information via reading. In all these cases, acceptable work or training performance usually requires that reading be done, under some degree of stress, for both speed and accuracy, either because of the real-time demands of the flow of work; the sheer volume of material to be read, understood, and remembered; or the severity of the consequences of misperception or misinterpretation (e.g., Ref. 13).

Unfortunately, however, human reading skills are not always sufficient to meet the demands of these various activities. Like any highly complex information-processing system, the efficiency of the reading process is influenced by a wide range of factors, including characteristics of the material to be read, the purpose for which reading is being done, the task environment in which reading takes place, the limitations on information processing faced by all human perceivers, and the reading ability and background knowledge of the individual reader. These facts suggest that the effectiveness of information-handling systems and training materials of all kinds can be improved if their design takes into account the nature of the reading process and the factors that influence its efficiency.

Studies of the reading process fall into four categories represented by entries in this *Engineering Data Compendium*: word recognition, eye movements, comprehension and memory, and text engineering or document design. In addition, there is considerable literature on individual differences in reading ability that can be consulted (Refs. 3, 12, 14, 19, 20, 21).

Word Recognition

Major issues in the study of word recognition include:

1. The nature and organization of the component mental processes or *encoding operations* that produce internal representations of a word's visual shape, pronunciation, and meaning (CRef. 8.110).
2. The factors that influence the speed and accuracy with which these internal representations or codes can be formed and decisions made about them (CRefs. 8.102, 8.103, 8.106, 8.107, 8.108, 8.209).
3. The facilitatory and inhibitory effects on encoding and decision making that result from expectations about upcoming words induced by text that has already been read (CRefs. 8.105, 8.109).

Methods used to study these issues include a variety of tasks that require specific kinds of decisions about words and other kinds of letter strings, especially *pseudowords* such as MARD, BREP, or TID, which are orthographically regular and pronounceable but unfamiliar and meaningless, and *random nonsense strings* such as RMAD, EPBR, or DTI, which lack orthographic structure and pronounceability as well as familiarity and meaning (CRefs. 8.102, 8.104, 8.106, 8.108). By comparing the efficiency of various kinds of decisions about these different kinds of letter strings, experimentation can determine what stimulus properties affect the operation of each encoding process and how the encoding processes interact to allow complete processing of a word for the purposes of any given task.

Because the tasks used in these studies are designed with theoretical goals to expose the component processes of word recognition, they differ in many ways from natural reading situations. Their empirical results transfer most directly to situations in which observers must make rapid decisions based on information conveyed by sets of single words or short phrases, and transfer less directly to situations in which observers read large amounts of connected discourse (Ref. 5).

Eye Movements

Issues addressed in the study of eye movements include the number, location, length, and variability of fixations and **saccades** as a function of text variables such as the number, length, familiarity, grammatical function, and predictability of the words (CRefs. 8.111-8.115; Ref. 15) and the processes by which information gleaned in different eye fixations is integrated to form a coherent internal representation of the text's contents and facilitate smooth, continuous reading (CRef. 8.116). As a part of studying these issues, researchers must make difficult decisions about which word or words are processed on any given eye fixation (Refs. 5, 15; CRef. 8.115).

Methods used to study eye movements in reading involve a variety of different techniques to monitor the direction of gaze while the reader is carrying out some reading activity, usually oral or silent reading of sentences or passages of text. Accurate monitoring of direction of gaze is a relatively high-technology enterprise that relies upon real-time data reduction by computer. Critical questions in evaluating eye movement research include both the spatial and temporal resolution power of the monitoring apparatus. Current state-of-the-art studies locate eye fixations within 0.333 deg of visual angle or less, and can sample eye position at least once per millisecond (Refs. 8, 11).

The experimental tasks of eye movement studies are often closer to natural reading situations than the tasks used in word recognition studies. Nevertheless, the monitoring apparatus, which requires that the head be held in a fixed position and sometimes involves spectacle-like headgear, imposes constraints on the reader that must be kept in mind in applying results to new situations. Generally speaking, however, application is not severely compromised by this problem.

Comprehension and Memory

Studies of comprehension and memory of text focus on issues that are somewhat analogous to those addressed in studies of word recognition, but at the level of major text constituents such as clauses, sentences, and the ideas they convey, rather than single words. Theoretical work concerns the nature and organization of the component mental processes that contribute to comprehension and memory (CRef. 8.128). Empirical work concerns: (1) the characteristics of text that affect the speed and accuracy with which it can be read, comprehended, and stored in memory (CRefs. 8.117, 8.118, 8.123, 8.124); (2) the influence of task demands and the reader's purpose on the efficiency of comprehension and memory processes (CRefs. 8.119, 8.120); and (3) the extent to which readers remember explicit information from a text in verbatim form, or remember an embellished and elaborated version of the text supplemented with inferences from background knowledge and other sources of information outside the text (Ref. 2; CRef. 8.125).

Methods used to study comprehension and memory usually involve: (1) presentation of a text to be read; (2) measurement of reading time, which can be done word by word (Ref. 1), sentence by sentence (Ref. 9), or passage by passage (Ref. 18); and (3) measurement of memory for the contents of the text, which can be done by administering a test of recognition memory (Ref. 17), a test of recall memory (Ref. 10), or by asking the reader to follow a set of instructions given in the text (Ref. 6).

These studies are often the closest of all to natural reading situations. Given that task demands and the reader's purpose do make a difference to results, care should still be taken when attempting to apply the results of comprehension and memory studies to new situations. As with studies of eye movements, though, application does not appear to be limited too seriously by such difficulties.

Text Engineering and Document Design

The goal of research on text engineering and document design is to discover techniques to improve the readability, comprehensibility, and memorability of text—especially expository and technical prose. Introductions to the voluminous literature on readability, which focuses on vocabulary choice and the construction of individual sentences, can be found in Refs. 7 and 16. Entries included in the *Engineering Data Compendium* summarize some of the work on organizational devices and comprehension aids used to supplement text, such as abstracts, summaries, advance organizers (CRef. 8.127) and review questions (CRef. 8.126). Methods used in research on text engineering and document design are much like those used in research on comprehension and memory, except that comparisons are made between versions of a text written at different levels of readability, or between versions that vary in the types of comprehension aids built into them. Given this similarity of method, the cautions on generalization of the results of text-engineering research are similar to those that apply to studies of comprehension and memory.

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Cross References

8.102 Factors affecting performance on same-different matching tasks with letter and word targets;

8.103 Same-different judgment of letter pairs: effect of type of letter match;

8.104 Letter recognition: effect of context;

8.105 Word recognition: effect of context;

8.106 Visual language processing of words and pictures;

8.107 Naming and classification speed for words and pictures;

8.108 Visual language processing of words and nonwords: effect of meaningfulness and pronounceability;

8.109 Visual language processing of words and letters: effect of priming;

8.110 Model of the word recognition process;

8.111 Eye movements during reading: effect of viewing distance;

8.112 Eye movements during reading and reading speed: effect of school grade level;

8.113 Eye movements during reading: effect of "local" text characteristics;

8.114 Eye movements during reading: effect of word length;

8.115 Guidelines for determining which words are processed on a given fixation;

8.116 Influence of parafoveal (nonfixated) information during reading;

8.117 Factors affecting reading time for sentences;

8.118 Reading speed: effect of semantic structure;

8.119 Reading speed: effect of reading task (comprehension or recall);

8.120 Reading speed and accuracy: effect of performing a concurrent task;

8.123 Reading speed and text memory: effect of information ordering;

8.124 Sentence comprehension: effect of syntactic structure;

8.125 Memory for inferences made during text reading;

8.126 Aids to text comprehension and recall: Review questions;

8.127 Aids to text comprehension and recall: summaries and advance organizers;

8.128 Schema theory of memory for text;

8.209 Pronunciation latency for words and pseudowords with typical or atypical pronunciation

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Notes

8.102 Factors Affecting Performance on Same-Different Matching Tasks with Letter and Word Targets

Table 1. Factors affecting performance on same-different matching tasks for letter and word matches.

Factor	Effect on Performance	Source
Letter Matches		
Type of match	When instructions are to match on name identity, physically identical letters give faster "same" responses than letters which are only name identical	CRef. 8.103
	When instructions are to match on category identity (vowels or consonants), the above relation remains true, and category matches are slower than physical or name matches	
Variation in irrelevant visual features	Differences in color, orientation, size, or contrast selectively retard "same" matches for physically identical pairs	CRef. 8.103
Performance of concurrent memory task	Instructions to remember an arbitrary set of letters interferes with matches of name-identical pairs	CRef. 8.103
Word Matches		
Type of targets	Words are matched more rapidly and accurately than random strings of letters; pseudowords (pronounceable but meaningless letter strings) are matched more rapidly and accurately than random letter strings	Refs. 2, 5
Number of letters in target string	Advantage of words over random strings increases as number of letters in string increases	Ref. 5
Case (upper versus lower) variations in target string	Where "same" pairs are identical and "different" pairs vary only in the case of one letter, words are matched faster than random strings	Ref. 9
	This advantage is as great as that found when "different" pairs are defined by a change of letters. Where "same" pairs contain many case transitions and thus do not preserve typical word shape, the word advantage diminishes	
Regularity of spelling patterns of strings	Regular strings as represented by words and pronounceable nonwords yield better performance on physical identity matches than unpronounceable but familiar acronyms (e.g., FBI, IBM)	Ref. 4
Familiarity/meaningfulness of targets	These factors are generally confounded	Ref. 4
	Familiarity appears to bias observer to "same" responses when familiar and unfamiliar strings are mixed	
	This response bias is eliminated by presenting only familiar-same and familiar-different pairs in one block of trials, and presenting unfamiliar pairs in a different block of trials	
Homophony and synonymy of targets	With physical identity instructions, difference judgments are not affected by homophony (i.e., cite, site is not slow relative to cite, mite); likewise, "different" responses are not affected by synonymy or other forms of semantic relatedness. New data suggest that insensitivity to phonological and semantic similarity may hold only when observers restrict their attention to the purely visual stimulus characteristics	Refs. 1, 2, 3, 9
	When rhyme-match instructions are compared with synonym-match instructions for word pairs, rhyme matches yield more rapid performance	Ref. 6

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Key Terms

Familiarity; letter perception; phonological matching; reaction time; reading; semantic matching; spelling regularity; visual matching; word length; word perception

General Description

Same-different matching tasks require an observer to determine, according to some criterion, if members of a pair of letters or words match one another. If they do, the observer responds "same" or presses a button marked "same." If they do not match, the observer responds "different" in a like manner. The criterion for a "same" response may vary across experiments. For example, "same" response may be required if:
(1) the pair members are physically identical (e.g., *A*, *A*);
(2) the pair members represent the same letter or word regardless of capitalization or typeface (e.g., *A*, *a*);
(3) the pair members rhyme;
(4) the pair members are synonyms; or
(5) the pair members belong to the same semantic or taxonomic category (e.g., both are fruits).

These are the five most commonly used dimensions; in general, a matching task can be used to assess human sensitivity to any dimension or property by which letters or letter strings can be discriminated from one another. For a given set of instructions regarding the criterion observers are to employ, stimulus pairs may have different levels of identity. For example, if the experimenter presents physically identical and name-identical pairs (e.g., *A*, *A*; *A*, *a*) in the same experiment with name-identical instructions, both pairs would elicit the "same" response. Physical-identity instructions would require a "same" response for (*A*, *A*) but a "different" response for (*A*, *a*). The table lists some factors that affect speed (a typical dependent variable in these experiments) and accuracy for "same" and "different" responses with letter and word pairs.

Applications

Diagnosing reading deficiencies related to knowledge of orthography (rules for legal sequencing of letters); development of lesson plans for better teaching of orthographic rules.

Constraints

- Because "same" and "different" are different responses as well as different word and letter pairs, the relative speed and accuracy of these alternatives are subject to observer's native or experimentally induced response biases.
- Although a wide number of stimulus and instructional variations could be made, particularly for word stimuli, many have yet to be investigated. Theoretical accounts of the general process by which matches are determined may help in making predictions about conditions that have not been investigated empirically (Refs. 7, 10, 11, 12).
- Results may be affected by reading skill.

Key References

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Cross References

8.103 Same-different judgment of letter pairs: effect of type of letter match;

8.108 Visual language processing of words and nonwords: effect of meaningfulness and pronounceability

8.103 Same-Different Judgment of Letter Pairs: Effect of Type of Letter Match

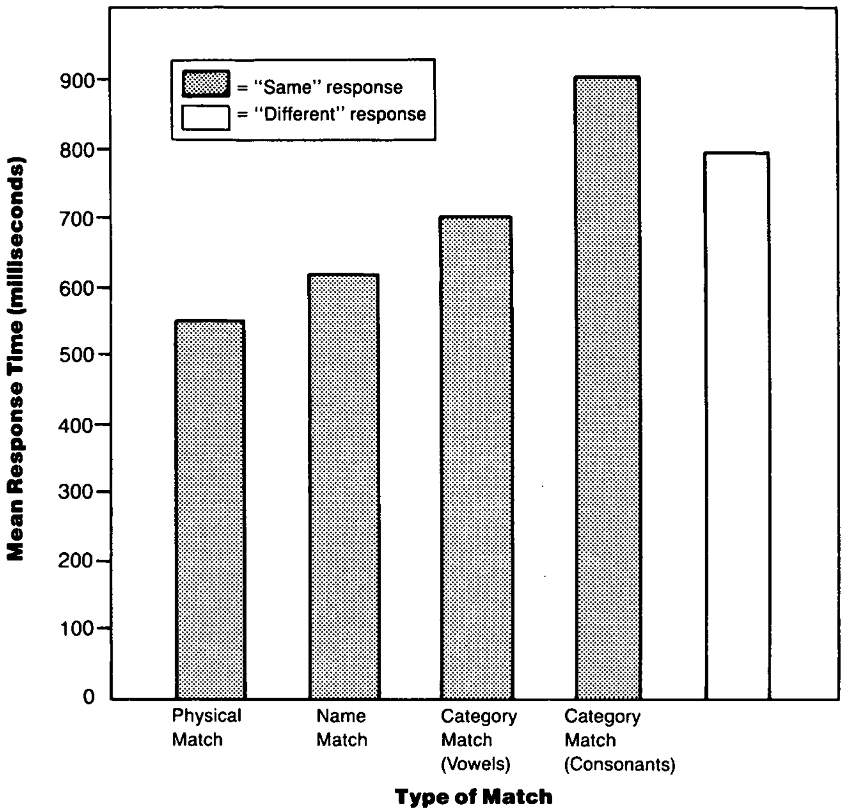

Figure 1. Mean time to respond whether both members of a letter pair belong to the same category (vowel or consonant) as a function of the levels of match between letters. (From Ref. 1)

Key Terms

Letter perception; reaction time; reading; semantic matching; visual matching

General Description

When observers are asked to judge whether two simultaneously presented letters belong to the same category (vowels versus consonants), decision latencies vary with the type of match between the letters. Physically identical letters produce the shortest latencies for "same category" responses. Letters which share the same name but differ in physical form (upper case versus lower case) yield intermediate latencies. Matches are slower still for letters matching only in category.

Applications

Diagnosing reading deficiencies related to knowledge of orthography (rules for legal sequencing of letters); development of lesson plans for better teaching of orthographic rules.

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Methods

Test Conditions

- Pairs of letters drawn using letter guide and Rapidograph #0-tip pen on 10.24 × 15.24 cm (4 × 6 in.) cards; letters drawn from set of upper and lower case *A*, *B*, *C*, *E*, *H*, *I*
- 84 cards per deck: 12 cards of physically identical letter pairs (e.g., *A*, *A*), 12 cards of name-identical letters (e.g., *A*, *a*), 24 cards of category-identical letters for the categories of vowel and consonant (e.g., *A*, *e*), 36 cards of non-identical letters (e.g., *A*, *B*)
- Cards subtended ~2.5 deg visual angle, presented for 1 sec, with 10-sec pause between trials
- Observers given accuracy and latency feedback after each trial

Experimental Procedure

- Reaction time task
- Independent variables: type of letter pair (physical, name, or categorical match)
- Dependent variable: response time (latency)
- Observer's task: press response key labelled "same" if both letters were vowels or consonants; otherwise press "different" key
- 3-5 observers, some practice

Experimental Results

- "Same category" responses are fastest for physical identical pairs and slowest for category matches. Latency for name-identical pairs is intermediate.
- "Same" responses are faster for vowel matches than for consonant matches.

Variability

- Standard deviations were not reported but have ranged from 10-30 msec in closely related studies (Ref. 1).

Repeatability/Comparison with Other Studies

The advantage of physical matches over name matches is well established, with the following constraints: differences between "same" and "different" responses are subject to factors that may bias one or the other response, such as the relative proportion of "same" and "different" responses in a block of trials.

Constraints

- The magnitude of the difference in response time for physical matches and for name matches varies considerably depending upon the presentation conditions. For example, differences between members of the letter pairs in irrelevant visual features—in particular, variation in color, contrast, size, and orientation — slow physical matches more than they do name matches (Ref. 2). If the observer is required to simultaneously remember an arbitrary set of letter names, then physical matches will be relatively unaffected but name matches will be slowed (Ref. 2).
- The physical identity advantage applies to simultaneous matches. When letters are presented successively (≥ 1-sec between letters) the advantage disappears (Ref. 2).
- Results may be affected by specific reading skills.

Key References

*1. Posner, M. I., & Mitchell, R. F. (1967). Chronometric analysis of classification. *Psychological Review*, *74*, 392-409.

2. Posner, M. I. (1978). *Chronometric explorations of mind* (pp. 27-56). Hillsdale, NJ: Erlbaum.

Cross References

8.102 Factors affecting performance on same-different matching tasks with letter and word targets;

8.108 Visual language processing of words and nonwords: effect of meaningfulness and pronounceability

8.104 Letter Recognition: Effect of Context

Key Terms

Letter recognition; practice; reading; semantic context; word superiority effect

General Description

Letters embedded in words and pseudowords (pronounceable but meaningless letter strings) are detected more accurately than letters embedded in random letter strings or letters presented in isolation where accuracy is limited by masking (the letter string is followed, or both followed and preceded, by a camouflaging noise pattern, typically consisting of randomly arranged line segments or letter fragments). This advantage for word contexts is known as the word superiority effect. Results appear to indicate that the whole pattern (a word) actually facilitates perception of the word's component parts (letters).

Methods

Test Conditions

- Target letters chosen from the target set *P, R, C, G*; four context conditions: (1) three-letter words (e.g., *POT, APE*), (2) unpronounceable nonsense strings (*PKS, SPL*), (3) one letter presented alone (*P*-blank-blank, blank-*P*-blank, or blank-blank-*P*), and (4) one letter presented with two noise characters which were always % (*P*%%, %*P*%, or %%*P*)
- Each target letter presented equally often in each of three display positions for all context types; stimuli typed on white index cards for brief presentation; letters subtended 0.3 deg vertically x 0.2 deg horizontally with a letter space separating letters
- Pre- and post-exposure mask consisted of randomly arranged letter fragments; mask subtended 1.5 deg of visual angle vertically, 2.8 deg horizontally
- Observers instructed to memorize target set before experiment began
- Initial session used to establish an exposure duration for each observer which produced approximately 60 % correct responses for each context
- Each of five experimental sessions consisted of two blocks of each context type counterbalanced within and between sessions (order of presentation controlled to distribute practice effects); each block consisted of two trials for each of the 12 stimuli in a context; stimulus occurrence was randomized
- Before each block, observers reminded of target letter and told which context type would occur
- Observers told whether each response was correct or incorrect

Experimental Procedure

- Four-alternative forced-choice identification task
- Independent variables: type of context, display position of target letter, number of sessions
- Dependent variable: percentage of targets correctly identified
- Observer's task: verbally indicate target letter present
- 10 adult observers
- 48 observations per condition

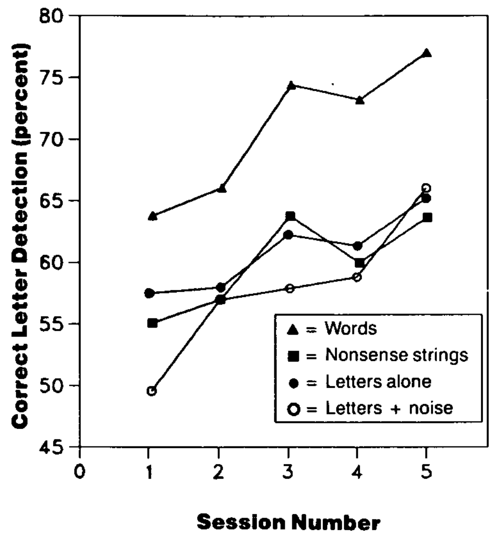

Figure 1. Percentage of letters correctly identified as a function of number of sessions (about 1 day apart) and type of context (word, letter string, noise, or no context [letter presented alone]). (From Ref. 1)

Experimental Results

- Target letters are identified more accurately in a word context than alone or in a nonword string or noise context ($p < 0.01$). There is no significant difference in performance with different nonword contexts.
- The advantage for word contexts persists across levels of practice ($p < 0.01$).
- The difference between words and the other contexts is most pronounced when the target letter is at the end positions of the display ($p < 0.01$).

Variability

Significance of independent variables and interactions assessed with a 4 x 3 analysis of variance. Post-hoc Newman-Keuls multiple comparisons performed to determine significance of accuracy among context types.

Repeatability/Comparison with Other Studies

The word superiority effect has been demonstrated in a number of studies. Experimental conditions that fail to demonstrate word superiority are presented in Constraints section.

Constraints

- When the target letter position is known in advance, the word advantage may be reduced or eliminated (Ref. 2).
- The word advantage disappears for large displays (>2 deg), especially if the target position is known in advance (Refs. 3, 4).
- The word advantage is more likely to occur when a visual noise mask replaces the target than when the display is unmasked and briefly presented (Ref. 2).
- Results may be influenced by specific reading skills.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Carr, T., Lehmkuhle, S. W., Kottas, B., Astor-Stetson, E. C., & Arnold, D. (1976). Target position and practice in the identification of letters in varying contexts: A word superiority effect. *Perception & Psychophysics, 19,* 412-415.

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Cross References

8.102 Factors affecting performance on same-different matching tasks with letter and word targets;

8.105 Word recognition: effect of context;

8.108 Visual language processing of words and nonwords: effect of meaningfulness and pronounceability;

Handbook of perception and human performance, Ch. 29, Sect. 4.1

8.105 Word Recognition: Effect of Context

Key Terms

Reading; semantic context; word recognition

General Description

Threshold exposure duration for words briefly presented on a screen (the minimum exposure time needed for recognition) is influenced by the degree to which a preceding context sentence indicates or does not indicate the target word. Table 1 shows representative contexts and target words. As shown by Fig. 1, a relevant context decreases the threshold exposure duration for target words while an irrelevant context increases threshold. The effect of context on threshold duration is well predicted by the degree to which the context permits an observer to guess the target word before it is presented.

Applications

Presentation of textual material on video display terminals; diagnosing and training poor readers; artificial intelligence simulation of word processing

Methods

Test Conditions

- Ten 9-letter target words with similar duration thresholds when tested with no context and the same word frequency (four per million); all words in uppercase letters
- Target presented as final word in congruous or incongruous context sentences of 0, 1, 2, 4, or 8 words (Table 1); length varied by removing words from beginning of context sentence; incongruous contexts taken from congruous contexts for other target words
- Target word initially exposed for 10 msec with duration increased by 10 msec until observer correctly identified word
- Background luminance 21.5 cd/m² (2 fc)
- Order of presentation counterbalanced across subjects to distribute practice effects, but congruous (*C*) and incongruous (*I*) trials mixed in fixed pattern: *CICCIICICI*
- Four practice trials; each observer performed task under all conditions

Experimental Procedure

- Ascending; method of limits
- Independent variables: congruity of context, length of context
- Dependent variable: threshold exposure duration
- Observer's task: correctly identify target word
- 10 female observers, median age 20 yrs

Table 1. Appropriate contexts and corresponding target words. (From Ref. 4)

Sentence No.	Context	Target Word
1	The actress received praise for being an outstanding	PERFORMER
2	Three people were killed in a terrible highway	COLLISION
3	The escaped soldier was captured and court-martialed for	DESERTION
4	Far too many people today confuse communism with	SOCIALISM
5	She likes red fruit jams of strawberry and	RASPBERRY
6	The skiers were buried alive by the sudden	AVALANCHE
7	Many colorful flowers and stately elms lined the	BOULEVARD
8	Medieval knights in battle were noted for their	GALLANTRY
9	More money buys fewer products during times of	INFLATION
10	The loud piercing screams occurred with regularly increasing	FREQUENCY

Contexts of less than eight words were formed by omitting the necessary number of words from the beginning of the sentence. Thus a relevant two-word context for the target *PERFORMER* is *an outstanding*. Irrelevant contexts for a given target word were formed from relevant contexts for other words.

Experimental Results

- Mean threshold exposure duration increases with the length of a preceding irrelevant, incongruous context, from ~70 msec with no context to ~95 msec with an eight-word (full sentence) context.
- Mean threshold exposure duration decreases with the length of a preceding relevant, congruous context, from ~70 msec with no context to ~45 msec for an eight-word (full sentence) context.
- Further study with 50 female subjects (i.e., decrease in threshold exposure duration) showed that the facilitative effect of context upon threshold is highly correlated with the observer's ability to guess the target word from the context ($r = -0.970$, $p < 0.01$ for an eight-word appropriate context).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Basic result has been replicated with other subjects (Ref. 4); other studies (Refs. 1-3) have extended results to the speed with which a word can be pronounced or categorized.

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Constraints

- Other factors such as word length and frequency affect duration threshold (CRef. 8.107).
- Facilitatory and inhibitory effects of context will be influenced by reliability of context as target-word predictor in a particular experimental situation.
- Results may depend on specific reading skills.

Key References

1. Fischler, I., & Bloom, P. A. (1979). Automatic and attentional processes in the effects of sentence contexts on word recognition. *Journal of Verbal Learning and Verbal Behavior, 18*, 1-20.

2. Stanovich, K. E., & West, R. F. (1979). Mechanisms of sentence context effects in reading: Automatic activation and conscious attention. *Memory and Cognition, 7*, 77-85.

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*4. Tulving, E., & Gold, C. (1963). Stimulus information and contextual information as determinants of tachistoscopic recognition of words. *Journal of Experimental Psychology, 66*, 391-327.

Cross References

8.107 Naming and classification speed for words and pictures;

8.109 Visual language processing of words and letters: effect of priming

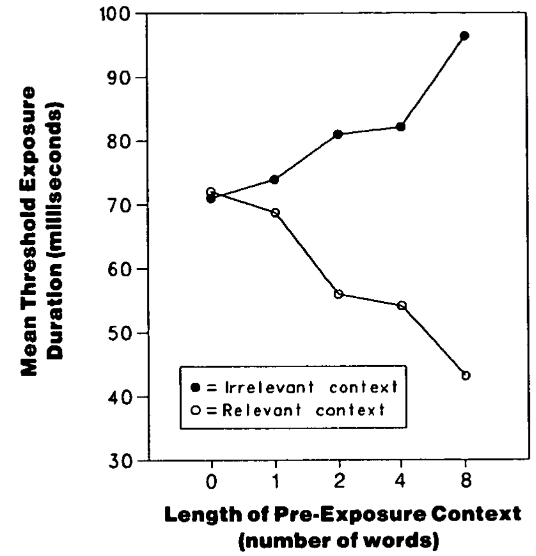

Figure 1. Mean threshold exposure duration for correct whole report of a target word preceded by relevant or irrelevant sentence context. Length of context was varied up to eight words (complete sentence). (Sample contexts are shown in Table 1.) (From Ref. 4)

8.106 Visual Language Processing of Words and Pictures

Table 1. Visual processing of words and pictures.

Experimental Paradigm	Relevant Variables	Experimental Outcomes	Source
Naming	Naming latency	Words are pronounced more quickly than pictures are named	Refs. 1, 3, 4 CRefs. 8.107, 8.109
	Exposure duration	Pictures are generally more accurately identified at shorter durations, but one study (Ref. 3) reports no effect. Complexity of picture is a crucial variable	Refs. 1, 2, 3 CRef. 8.107
Categorization	Categorizing latency	Pictures are categorized more quickly than words, although magnitude of effect is less than naming advantage for words	Ref. 3 CRef. 8.107
Stroop naming	Congruence of stimulus pair	Latency to name pictures decreases when congruent word is presented at the same time; when an incongruent word is presented, latency increases considerably (by 200 msec) relative to latency when no concurrent stimulus is presented. Congruence of concurrently presented pictures does not affect naming latency for words	Ref. 4 CRef. 8.109
Stroop categorizing	Congruence of stimulus pair	Simultaneous presentation of an incongruent picture increases word classification latency by 200 msec. Congruence of a simultaneously presented word does not affect picture classification latency. A categorically related prime, whether word or picture, reduces classification latency for a word or picture target	Ref. 4 CRef. 8.109
Priming, naming	Exposure duration of prime	Picture primes produce the greatest priming effect when exposed for short durations for both picture and word targets. (Priming is measured by the reduction in latency produced by categorically related prime relative to a categorically unrelated prime)	Ref. 1
		Picture targets benefit more from priming than do word targets at all durations. Priming advantage increases with exposure duration of prime, but effect is more marked for words than for pictures	

Key Terms

Categorization latency; naming latency; picture recognition; priming; pronunciation latency; reading; stroop effect; word recognition

General Description

Studies using a variety of experimental paradigms indicate that the meaning of a picture of a common object is determined more quickly than the meaning of the printed English word for that object. Conversely, the name of a pictured object is given less quickly than a written word is pronounced. The table summarizes a number of studies suggesting that written words and pictures are probably not processed alike. All of the experimental paradigms require a target word or picture to be categorized or named. (In the categorization task, the category is known beforehand, and the subject indicates whether the target item is a member of that category.)

In naming or categorization tasks, the target is presented alone and time to name or categorize it (latency) is recorded. In Stroop paradigms, the target is presented with a stimulus of the opposite type (word with picture or vice versa). The non-target may be congruent (requiring the same response as the target) or incongruent (requiring a different response). In priming paradigms, the target is briefly preceded by a non-target of the same or different type (i.e., word or picture). Primes may be congruent or incongruent.

Applications

Design of graphic and instructional material; artificial intelligence simulation of word processing.

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Constraints

- These results are specific to English and probably only generalizable to languages that use a phonetic alphabet.
- While words are printed in a fairly standardized form, pictures encompass a wide variety of representations. These results apply to simple outline drawings of common objects that are easily identifiable.

Key References

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Cross References

8.107 Naming and classification speed for words and pictures;

8.109 Visual language processing of words and letters: effect of priming

8.107 Naming and Classification Speed for Words and Pictures

Key Terms

Categorization latency; naming latency; picture recognition; reading; word recognition

General Description

Subjects take longer to name a line drawing of a common object than to pronounce the printed word that names the object. This response time advantage for words over pictures is reversed if the subject's task is to decide whether the object represented by a word or picture belongs to a particular category of objects, such as furniture. For this task, judgments about pictures are faster.

Applications

Design of graphic and instructional material; artificial intelligence simulation of word processing.

Methods

Test Conditions

- 96 line drawings of common objects or their names in Berlin 14-point lower-case press-off letters; objects from 18 categories of 2-9 items each
- Each observer saw half the objects as line drawings and half as words; 800 msec before item was presented, experimenter said "ready" (Conditions 1, 2) or named a category (Condition 3)
- Item exposed in tachistoscope for 250 msec (Conditions 2, 3) or 40, 50, 60, or 70 msec in random order (Condition 1), with each item presented equally often at each duration

Experimental Procedure

- Method of constant stimuli (Condition 1); reaction time (Conditions 2, 3); between-subjects design
- Independent variables: task instructions, exposure duration (Condition 1), mode of representation (picture or word)
- Dependent variables: latency of naming or classification response (Conditions 2, 3); duration threshold, defined as duration at which subjects could correctly name or read items on 50% of trials (Condition 1)
- Observer's task: name object or word presented (Conditions 1, 2) or respond yes or no to indicate if item belonged to specified category (Condition 3)
- 16 observers in Condition 1, 8 in Condition 2, and 16 in Condition 3; different observers participated in each condition

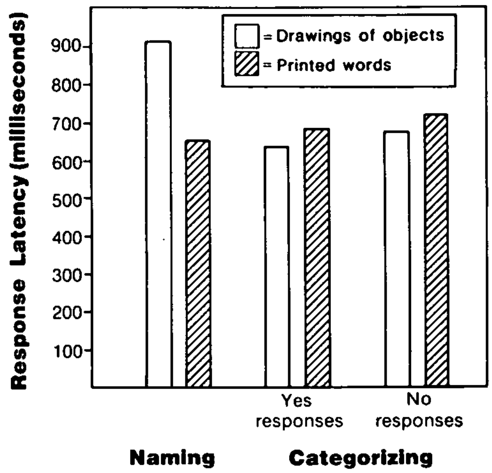

Figure 1. Mean time required to name and classify (verify category membership of) printed words and line drawings of common objects. (From Ref. 2)

Experimental Results

- Words are named more quickly than are pictures, but pictures are categorized more quickly than are words.
- Pictures are categorized faster than they are named, whereas the opposite is true for words.
- Threshold exposure durations were approximately equal for the word and picture targets (46 msec and 44 msec, respectively); thus the two types of targets were equally discriminable as visual patterns.

Variability

All 8 observers had a greater latency for picture-naming than word-naming in Condition 2 ($p<0.01$, sign test). Standard error of the mean difference (260 msec) was 91 msec. Of 16 observers, 14 showed greater latency for word categorization than for picture categorization ($p<0.01$). Standard error of the mean difference (51 msec) was 42 msec.

Repeatability/Comparison with Other Studies

The difference in naming latencies for words and pictures has been confirmed in other studies (Ref. 1). The categorization effect is consistent with results from other types of tasks such as the Stroop paradigm (CRef. 8.106). In this paradigm, the target is presented simultaneously with a non-target stimulus of a different type (e.g., word with picture or vice versa), and the non-target may be congruent (requiring same response as the target) or incongruent (requiring a different response).

Constraints

- Some studies have shown exposure duration required for a given level of accuracy to be shorter for pictures than for words (Ref. 1).
- Size, contrast, familiarity, confusability with other items, etc., may affect identification accuracy with brief exposure; some of these variables are difficult to equate for such disparate materials as line drawings and words. However, even for stimulus sets that show more accurate identification at brief exposures for pictures, naming latency is still greater for pictures than for words.
- These results are specific to English and are probably generalizable only to languages that use a phonetic alphabet.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

8.106 Visual language processing of words and pictures;

Handbook of perception and human performance, Ch. 29, Sect. 3.2

8.108 Visual Language Processing of Words and Nonwords: Effect of Meaningfulness and Pronounceability

Table 1. Visual processing of letter strings varying in meaningfulness and pronounceability.

Task	Measure	Results	Source
Pronunciation	Latency to pronounce a string of letters flashed on a screen	Words are pronounced more quickly than pseudowords, and common words more quickly than rare words.	Ref. 4 CRef. 8.209
Pronounceableness judgments	Latency to make a yes/no decision about the pronounceableness of a letter string	Words are more quickly judged than pseudowords. Both these "yes" decisions are faster than "no" decisions	Ref. 3
Meaningfulness judgments	Latency to make a yes/no decision about the meaningfulness of a letter string	Words are more quickly (by ∿100 msec) judged "yes" than are acronyms. Random letter strings are more quickly (by ∿100 msec) judged "no" than are pseudowords. "No" judgments are slightly quicker (by ∿15 msec) for random letter strings than "yes" judgments are for acronyms	Ref. 3
Lexical decision	Latency to make a yes/no decision about whether a letter string is a word	"No" judgments for acronyms and random letter strings are faster than "no" judgments for pseudowords. Words are judged more slowly than are random letter strings and acronyms, but faster than pseudowords. However, pseudowords are judged more accurately	Ref. 3
Forced-choice recognition; letter string is briefly flashed on screen; observer is then presented with the identical string and a similar string (different by one letter), and must choose the previously viewed string	Recognition accuracy	Words are recognized more accurately than are pseudowords or random letter strings, whether expected or not. Pseudowords are recognized more accurately than are random letter strings only when they are expected. If pseudowords are presented intermittently in a block of trials where random letter strings are expected, there is no difference in accuracy between the two	Refs. 1, 2
Whole report: a letter string is briefly flashed on screen and observer must reproduce it	Reproduction accuracy; an error is recorded if any letter is erroneously reported	Words and pseudowords are more accurately reproduced than are random letter strings	Ref. 5
Same-different matching: a pair of letter strings is flashed together on screen. Observer must decide as quickly as possible whether they are identical or different	Latency and accuracy of same-different judgments	In blocked trials (one stimulus type per block), words and pseudowords are judged faster and more accurately than are acronyms and random strings	Ref. 3 CRef. 8.102

Key Terms

Letter perception; letter recognition; lexical decision latency; pronounceability; pronunciation latency; reading; word perception; word recognition

General Description

On many visual tasks in which subjects must process letter strings, performance varies with the meaningfulness and pronounceability of the letter string. The table summarizes performance on a variety of such perceptual tasks. Four types of letter strings may be used: (1) words, which are pronounceable and meaningful; (2) pseudowords, which are pronounceable but not meaningful; (3) acronyms, such as FBI, which are meaningful but not pronounceable; and (4) random letter strings, which are neither meaningful nor

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pronounceable. A variety of tasks have been used to assess differences in the processing of these four types of letter strings. For example, subjects may be asked to pronounce a string of letters flashed on a screen, judge whether a given letter string is pronounceable or meaningful, or decide whether a letter string is a word (lexical decision task). Not all tasks have been tested with each string type. Generally, in these experiments, either speed or accuracy of task performance is the dependent measure. When speed is the measure, accuracy generally is recorded also. Accuracy results for tasks that emphasized speed are not reported unless they are inconsistent with the ordering of performance by speed, that is, when fast performance is relatively inaccurate rather than relatively accurate.

Applications

Design of graphic and instructional materials and displays; diagnosis of reading deficiencies related to knowledge of orthography (rules for sequencing of letters); artificial intelligence simulation.

Constraints

- Results of same-different tasks are complex when words, pseudowords, acronyms, and random letter strings are mixed within trial blocks (that is, when subjects did not know in advance which of the four types of stimuli to expect on a given trial) (Ref. 3). These and similar effects show that the subject's processing strategy may affect results. These variables have not been fully explored.
- Poor readers might not show the same effects.

Key References

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Cross References

8.102 Factors affecting performance on same-different matching tasks with letter and word targets;

8.209 Pronunciation latency for words and pseudowords with typical or atypical pronunciation

8.109 Visual Language Processing of Words and Letters: Effect of Priming

Table 1. Effects of priming in visual language tasks.

Factor	Effect on Priming	Source
Naming Task		
Picture versus word primes	Picture primes are effective at shorter onset asynchronies than word primes	Ref. 4
Picture versus word targets	Related primes, whether pictures or words, are more effective with picture targets	Ref. 4
Lexical Decision Task		
Physical adjacency of prime to target	A word interpolated between two related primes does not affect priming on a simultaneous lexical decision task	Ref. 10
Consecutiveness of prime and target	Priming still has a facilitative effect when words intervene between prime and target	Ref. 1
Category shifting	Facilitation and inhibition are seen with category-shifted primes, just as with valid related primes, but facilitation is not seen at short inter-stimulus onset asynchronies	Ref. 8
Primes consisting of superordinate category names	Unrelated primes are inhibitory, but related primes produce little facilitation	Ref. 2
Antonym primes	Related primes produce facilitation, but unrelated primes produce little inhibition	Ref. 2
Backward association	Backward association, such as yard as a prime for barn, produces facilitation during early trials; later trials show more facilitation when association is forward (barn as a prime for yard)	Ref. 6
Low-frequency targets	Priming is greater, i.e., both facilitation and inhibition are greater, for low-frequency target words than for higher-frequency words	Ref. 11
Visually degraded and low-illumination targets	Facilitation due to priming is increased for degraded targets	Refs. 3, 7
Syntactic primes	Appropriate syntactic context facilitates performance when all primes are syntactic, but not when syntactic primes are randomly mixed with semantic primes	Ref. 5
Same-Different Matching Task for Letters		
Validity of prime	For valid primes, related primes facilitate matching, whereas related primes inhibit matching For invalid primes, related primes facilitate matching, but unrelated primes have no effect Facilitation effects seen at interstimulus onset asynchronies of <100 msec, but inhibition requires long asynchronies (>300 msec)	Ref. 9

Key Terms

Interstimulus onset asynchrony; lexical decision latency; naming latency; picture perception; priming; reading; semantic context; word frequency; word recognition

General Description

Priming refers to the influence of an immediately preceding context on the processing of a briefly presented target. Typical tasks in which the effects of priming are assessed include naming tasks (in which the subject must name the target presented), lexical decision tasks (in which the subject must determine whether a target letter string is a word), and same-different matching tasks (in which the subject

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must state whether two targets presented simultaneously are the same or different).

In a typical priming experiment, the prime is first presented, followed a short time later by the target. The prime is usually turned off before the target word appears. (The two are presented together, however, in simultaneous lexical decision tasks, in which the subject must decide whether the prime and the target are both words.) The prime may be a letter or one or more words; the target is typically a word or letter. Pictures may also be used as primes and/or targets. The interval between the onset of the prime and the onset of the target (the interstimulus onset asynchrony) is usually <1 sec. The effect of priming may vary with onset asynchrony.

The prime may be either related to the target along some dimension, unrelated to the target, or neutral. For example, a word prime may belong to the same semantic category as the target word, e.g., both may be items of furniture (related prime), the prime may belong to a different semantic category (unrelated prime), or it may have no sematic content (neutral prime). Primes may be valid or invalid. A valid prime is one which provides predictive information about what the target is likely to be on a given trial; an invalid prime is one which holds no predictive information. For example, a prime consisting of a category name is valid if the target word following it is very likely to be a member of that category (or very likely not to be a member of that category); it is invalid if there is no relation between the category given in the prime and the target word. Subjects are often informed beforehand whether the primes in a given block of trials are valid or invalid. Sometimes elaborate mapping rules are used; for example, when category *A* appears as a prime, this may signal that the target word is likely to be a member of category *B* (category shift).

Response time is generally faster when primes are related to the targets that follow them than when primes are unrelated or neutral. In some circumstances, such facilitation is seen even when the primes are not valid. Unrelated primes may cause inhibition under certain conditions (response time is increased relative to response time with neutral primes).

Table 1 summarizes the effects of several factors on priming.

Applications

Design of graphic and instructional materials; diagnosing and training poor readers; artificial intelligence simulation of word processing.

Constraints

- Results may be affected by reading skill and background knowledge.

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Cross References

8.105 Word recognition: effect of context;

8.106 Visual language processing of words and pictures;

8.107 Naming and classification speed for words and pictures

8.110 Model of the Word Recognition Process

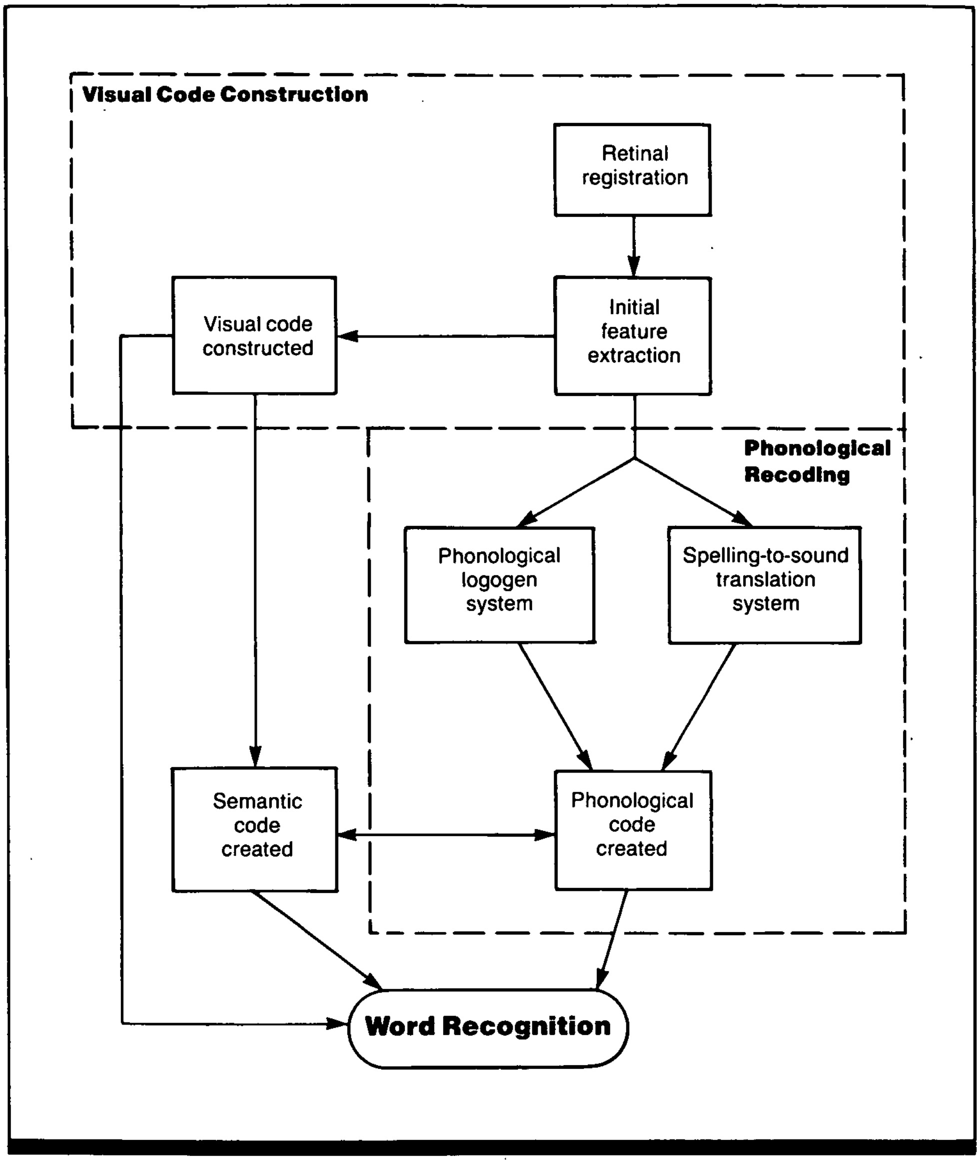

Figure 1. Characterization of the word recognition system that seems to be the most consistent with currently available data. Boxes represent the two component processes, and arrows represent information flow. Note the parallel organization of the component processing mechanisms: there are multiple paths, rather than a single series of steps, by which input can flow from retinal registration to word recognition. Because of its parallel organization, this is called a "horserace" or "multiroute" model of the system, with each of the multiple paths consisting of a "horse" in the "race" to achieve word recognition.

Key Words

Reading; word recognition

General Description

Figure 1 illustrates a contemporary model of the process involved in recognizing a printed word. The process involves some early stages common to all forms of visual pattern recognition, such as retinal registration (image projection to the **retina**) and initial feature extraction (perceiving characteristics of image, such as the shape and size of individual letters). These stages are followed by information-processing mechanisms specific to the reading process; at least two major pathways are involved. One is a rather direct pathway from a visual code for the word (which constitutes a relatively complete and well-integrated image or physical description of the word as a visual pattern) to the semantic idea and recognition. This is reading without speech recod-

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ing. An alternative pathway, phonological recoding, is more indirect; in it, the visual code for the word is recoded into a phonological code corresponding to its pronunciation, and then the meaning is accessed through the same pathway by which the meaning of speech is recognized. This indirect pathway may be particularly important for inexperienced or poor readers.

The process of phonological recording itself allows alternate pathways. The pronunciation of the word may be attained either through the phonological logogen system (a set of whole-word, template-like structures that provide direct access via association from the visual code to the full pronunciation of the word) or through a set of spelling-to-sound translation rules (also called grapheme-to-phoneme conversion rules) that embody the rules of English pronunciation for letter strings. These rules enable one to pronounce novel and unfamiliar letter strings in ways that are fairly consistent from speaker to speaker. The existence of these two pathways has been demonstrated by experiments comparing performance with words and with pronounceable but meaningless letter strings called pseudowords (CRef. 8.108).

Empirical Validation

The model is based upon empirical evidence that visual, phonological, and semantic codes exist to represent information about words and that the reader can devise strategies that favor one code over others. Thus, the reader can, to some extent, control the role of the pathways in word recognition. Studies of the word superiority effect, in which letters are perceived more accurately when they are embedded in words than in nonwords (CRef. 8.104), indicate that while homophones (words pronounced alike but different in meaning) as response alternatives (e.g., *cell* and *sell*) normally lead to poor performance, typical word-superiority performance reappears if the reader expects homophones (Ref. 3). This implies that readers ordinarily use phonological codes in this letter-recognition task and hence cannot decide which answer is correct if the two alternatives sound the same. If, however, they know in advance that they will have to make such discriminations, they can switch to other codes, possibly relying on a direct visual route to a semantic code, to avoid confusion. This strategic flexibility is inconsistent with the existence of separate visual-to-semantic and phonological encoding pathways.

Strong evidence for two phonological pathways is provided by forms of aphasia that cause individuals to be unable to pronounce pseudowords and novel words despite intact ability to pronounce familiar words (phonological logogen system intact, spelling-to-sound translation system damaged) (Refs. 1,2).

Applications

Design of graphic and instructional materials; artificial intelligence simulation of word processing.

Constraints

- The model does not specify the boundary conditions for strategic control over particular pathways, for experimental studies only provide information about very specific, controlled situations.
- The model was developed largely for English words and native speakers of English. Because it applies only to alphabetic languages, subtle differences in pathway reliance for other languages are certainly possible.

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Cross References

8.104 Letter recognition: effect of context;

8.108 Visual language processing of words and nonwords: effect of meaningfulness and pronounceability

8.111 Eye Movements During Reading: Effect of Viewing Distance

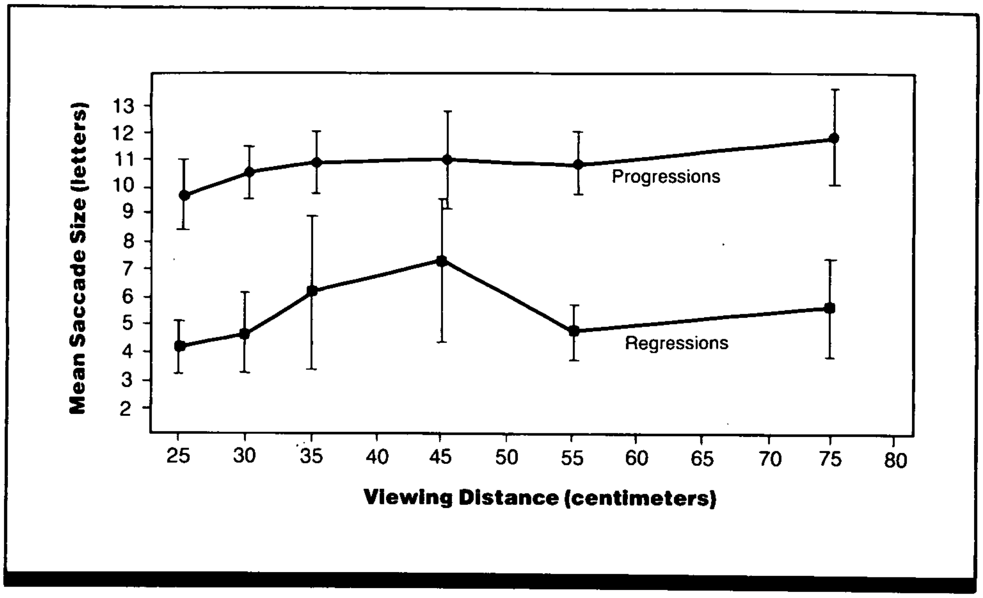

Figure 1. Mean saccade size (in number of letters) as a function of viewing distance for progressions (left-to-right saccades) and regressions (right-to-left saccades). (From Ref. 3)

Key Terms

Eye movements; fixation duration; reading; saccadic eye movements

General Description

In text reading, the eyes jump from position to position in a series of eye movements called **saccades**. The pauses between these movements, during which the eyes are fixated on a particular position in the text, are periods of information intake during which text is processed perceptually. Eye movements are generally left to right across a line in a left-to-right language such as English, but occasional right-to-left regressive movements are seen. At the end of a line, the eye moves in a sweep to the beginning of the next line. Average saccade length changes with viewing distance (distance between reader and text) to maintain an approximately constant average number of letter spaces between fixation pauses and a constant average number of fixations per line. However, at any given viewing distance, there is substantial variability around these mean values. At the same time, average fixation duration increases slightly with viewing distance, reflecting greater demands upon acuity at the longer distance. Again, there is considerable variability.

Applications

Diagnosing and training poor readers; artificial intelligence simulation.

Methods

Test Conditions

- Six text paragraphs with letter size of ~2.5 mm
- Viewing distances of 25-75 cm
- Observer read a different paragraph at each viewing distance (total of six trials)

Experimental Procedure

- Latin square design, matching specific paragraphs and viewing distances
- Independent variable: viewing distance
- Dependent variables: length and direction of saccade, fixation duration
- Observer's task: read each paragraph at a different distance
- 6 observers

Experimental Results

- While saccade size (measured in deg of visual angle) changes substantially with viewing distance, it changes little in terms of letter spaces, with each progressive saccade measuring ~10 letter spaces (Fig. 1).
- Progressive (left-to-right) saccades are longer at all distances than are regressive (right-to-left) saccades.
- Average fixation duration increases with increasing distance: the range is 195-220 msec for fixations following progressive saccades, 175-205 msec for fixations following regressions (Fig. 2).

Variability

Vertical bars (Figs. 1, 2) represent the 95% range of saccade lengths and fixation durations at each distance.

Repeatability/Comparison with Other Studies

Similar values for saccade size and fixation duration are found for a large sample at a fixed distance (Ref. 1). Reference 2 found shorter fixations prior to and following regressions.

Constraints

- Text characteristics, as well as individual differences and reading skill, influence saccade length and fixation duration (CRefs. 8.112, 8.113, 8.114, 8.116).
- At extremely close viewing distances, and for short durations, **accommodation** and **visual acuity** affect the results.

Key References

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Cross References

8.112 Eye movements during reading and reading speed: effect of school grade level;

8.113 Eye movements during reading: effect of "local" text characteristics;

8.114 Eye movements during reading: effect of word length;

8.115 Guidelines for determining which words are processed on a given fixation;

8.116 Influence of parafoveal (nonfixated) information during reading

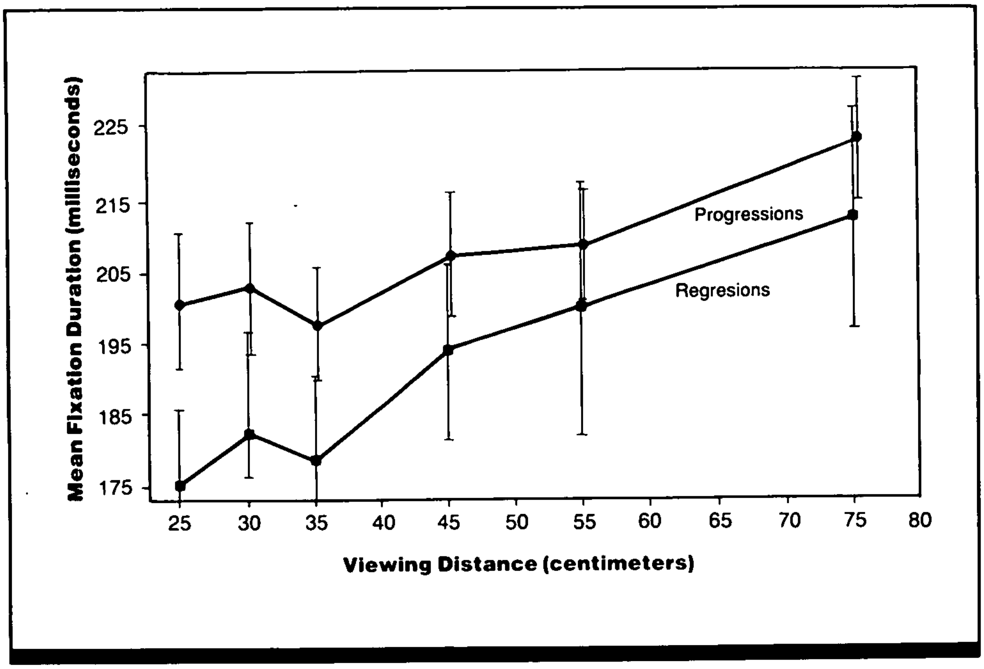

Figure 2. Mean fixation duration as a function of viewing distance for progressions (left-to-right saccades) or regressions (right-to-left saccades). (From Ref. 3)

8.112 Eye Movements During Reading and Reading Speed: Effect of School Grade Level

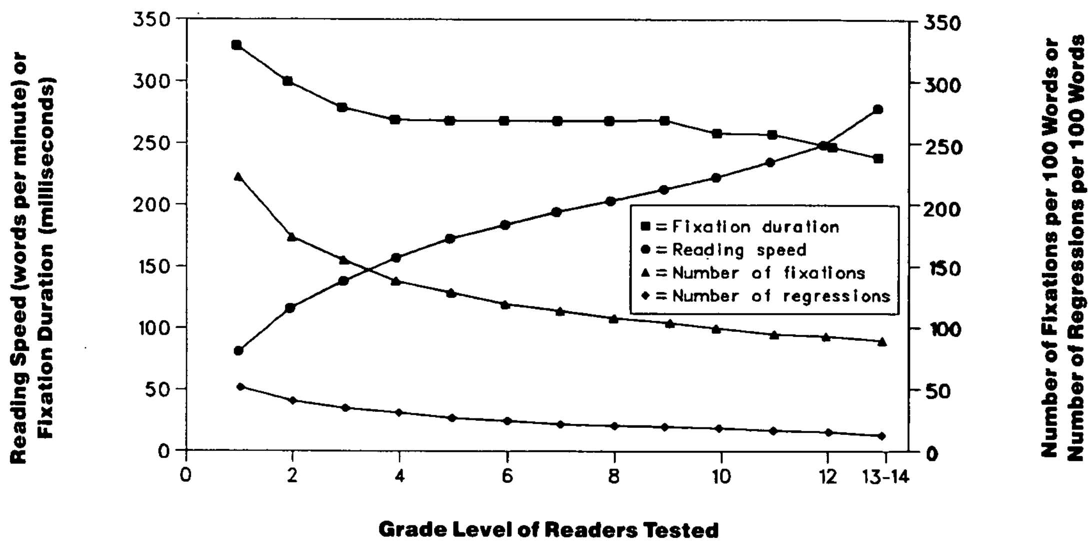

Figure 1. Mean reading speed, mean fixation duration, mean number of fixations per 100 words, and mean number of regressions (right-to-left eye movements) per 100 words as a function of the school grade level of readers. As speed increases with grade level, fixation duration, number of fixations, and number of regressions all decrease, though not at the same rates. (From *Handbook of perception and human performance*, adapted from Ref. 1)

Key Terms

Eye movements; fixation duration; fixation frequency; fixation regression; reading speed

General Description

As children and young adults progress through school, their skill in reading connected prose increases. A number of measures associated with increased skill, such as reading speed, may be obtained from eye movement records. Fixation duration and number of fixations decline most dramatically in grades 1-4 and decline more slowly throughout the upper grades. Reading speed increases throughout grades 1-12, and number of regressions (eye movements back to text already read) declines throughout these grades.

Applications

Design of graphic and educational materials for different age groups. Selection of personnel for jobs that require a particular level of reading skill.

Methods

Test Conditions

- Reading material of mid-year difficulty for each grade
- Selective questions on content of passages to test comprehension
- Eye movements measured by EDL Reading Eye Camera, which records eye movements by light reflected off the eye; head fixed in place by chin-forehead rest

Experimental Procedure

- Independent variable: school grade of reader
- Dependent variables: number of fixations, fixation durations, number of regressions, time taken to complete passage as indicated by film record
- Observer's task: read passage for comprehension; take comprehension test
- 12,143 observers from grades 1-14 (grade 14 is equivalent to college sophomore level), <1000 observers per grade level, all observers of average socioeconomic level, >10% from private or parochial schools
- Results for first-graders restricted to those capable of silent reading with comprehension for material of 1.8 grade-level difficulty
- Only data from observers capable of 70% comprehension reported in results

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Experimental Results

- Average number of fixations per 100 words declines from 224 at grade 1 to 90 for college freshmen and sophomores.
- Average number of regressions per 100 words declines from 52 to 15 over the same grade span.
- Average fixation duration declines from 330 to 240 msec from the lowest to the highest grade.
- Average reading speed (with comprehension) increases from 80 to 280 words/min from the lowest to the highest grade.

Variability

No information on variability was given.

Constraints

- Readers were tested with different materials at different grade levels. A variety of textual variables affect reading time and eye movement during reading (CRef. 8.113, 8.114, 8.116, 8.117).
- Considerable individual variations in reading skill occur within all age groups.
- Average levels of performance may vary slightly for current students; data reported are from 1960 publication (Ref. 2).
- Results may be influenced by the task demands (i.e., reading in preparation for a comprehension test).

Key References

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Cross References

8.113 Eye movements during reading: effect of "local" text characteristics;

8.114 Eye movements during reading: effect of word length;

8.115 Guidelines for determining which words are processed on given fixation;

8.116 Influence of parafoveal (nonfixated) information during reading;

8.117 Factors affecting reading time for sentences;

Handbook of perception and human performance, Ch. 29, Sect. 5.1

8.113 Eye Movements During Reading: Effect of "Local" Text Characteristics

Table 1. Effects of text and word characteristics on fixation duration and saccadic eye movements during reading. (Adapted from Ref. 3)

Factor	Effect upon Fixation Duration/Saccadic Eye Movements	Source
Word frequency	Low-frequency words and words of lower familiarity fixated longer Fixation duration influenced by frequency of words near to word directly fixated	Refs. 2, 7
Word length	Fixation duration longer on shorter words; but multiple fixations more likely on longer words Saccade length longer when a longer word lies to right of fixation Saccade length longer following fixation on a longer word	Refs. 2, 4 CRef 8.114
Misspellings	Fixation duration longer for misspelled words Saccade length shorter when words in near periphery are misspelled	Ref. 5
Replacement of letters by grating pattern (parallel bars)	Fixation duration longer when grating is substituted	Ref. 8
Contextual constraint upon words	Fixation duration shorter for words that are highly redundant or highly constrained by text	Ref. 3
Significance of words to meaning of text	Fixation duration longer and saccade length shorter with more regressions (right-to-left movements) in areas where words are important to meaning of text	Ref. 9
Grammatical class of word	Fixation longer on verbs than function words (e.g., *the*) of equivalent length Fixation less likely on function word Regressive saccades (right-to-left eye movements) are more likely after encountering a pronoun (e.g., *she, it*)	Refs. 4, 5, 7 CRefs. 8.114, 8.116
Position of word on line	Fixation duration shorter after corrective saccade following return sweep Fixation duration longer for first fixation on line, shorter for final fixation on line	Ref. 7
Numbers	Fixation duration longer for numbers whose names have more syllables	Ref. 6
Number of fixations on word	Multiple fixations of shorter duration than single fixation	Ref. 2 CRef. 8.114
Fixation position within word	Fixations shorter at beginning and end of word relative to center	Ref. 5
Non-word elements	Fixations less likely and shorter between sentences and in blank space	Ref. 1

Key Terms

Eye movements; fixation duration; reading; saccadic eye movements; word frequency; word length

General Description

Characteristics of connected text and individual words influence the duration and likelihood of fixations and **saccades** (eye jumps from one fixation point to another) during reading. The influence of these characteristics can be measured by recording eye movements as text is read. Text is generally presented on a video display screen, and the observer reads it with head immobilized (using a chinrest) as

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the direction of gaze is recorded using scleral-reflectance or other monitoring equipment (CRef. 1.904). The table summarizes the effect of a number text and word characteristics on fixations and saccadic eye movements.

Applications

Diagnosis and training of poor readers; artificial intelligence simulation of word processing.

Constraints

- Many of these factors are spuriously correlated in normal text (e.g., word length negatively correlates with word frequency). Such correlations make caution necessary in interpretation.
- The number and duration of eye fixations depends on the skill level of the reader (CRef. 8.112).

Key References

1. Carpenter, P. A., & Just, M. A. (1977). Reading comprehension as eyes see it. In M. A. Just & P. A. Carpenter (Eds.), *Cognitive processes in comprehension* (pp. 109-139). Hillsdale, NJ: Erlbaum.

2. Kliegl, R., Olson, R. K., & Davidson, B. J. (1983). On problems of unconfounding perceptual and language processes. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 333-343). New York: Academic Press.

*3. McConkie, G. W. (1983). Eye movements and perception during reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 65-96). New York: Academic Press.

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Cross References

1.904 Methods of measuring eye movements;

8.111 Eye movements during reading: effect of viewing distance;

8.112 Eye movements during reading and reading speed: effect of school grade level;

8.114 Eye movements during reading: effect of word length;

8.116 Influence of parafoveal (nonfixated) information during reading

8.114 Eye Movements During Reading: Effect of Word Length

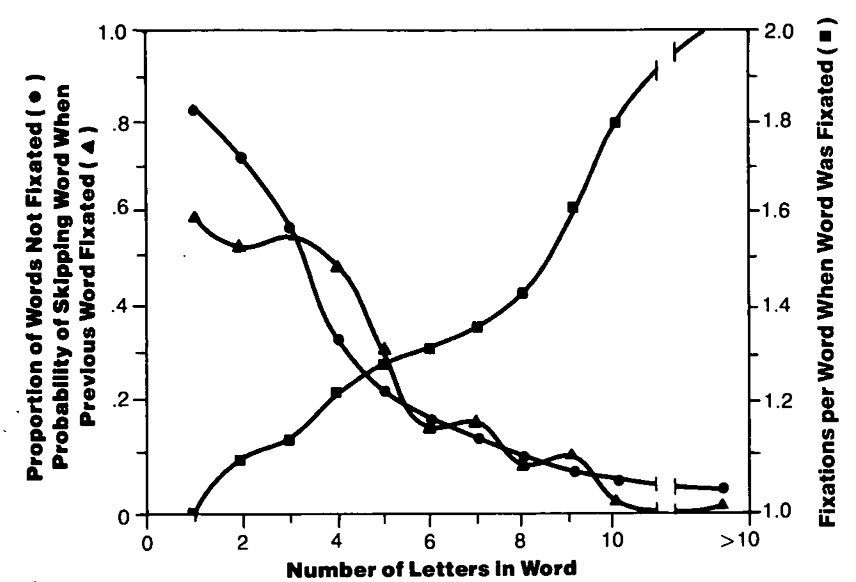

Figure 1. Eye fixations during reading as a function of word length. Figure plots data of Table 1 of Ref. 1 showing proportion of words not fixated, probability of skipping a word when the word to the left was previously fixated after a progressive (left-to-right) movement of the eyes, and fixations per word when word was fixated for words of different length. (Data from Ref. 1)

Key Terms

Eye movements; fixation frequency; reading; visual fixation; word length

General Description

The eye fixations made during the reading of connected text vary as a function of the length of the word. If a word is fixated at all, the number of fixations per word increases with word length (averaging one fixation per word for one-letter words, and increasing to an average of two fixations per word for words >10 letters). The probability that a word will *not* be fixated is 0.4, averaged over words of all lengths, but this too varies considerably with word length, from 0.85 for words of one letter to 0.08 for words of >10 letters. This relationship is partially explained by the strong tendency not to fixate function words (*the, and, am, a,* etc.), which generally average fewer letters than content words. However, ~25% of the non-function content words are also skipped. For example, the fixated word and the word to its right are often read during a single fixation, precluding the need to fixate once for each word (parafoveal preview) (CRef. 8.116). This finding implies that data which associate word processing with the amount of time spent fixating a word should be interpreted cautiously (CRef. 8.115).

Applications

Interpretation of eye movement records during reading; artificial intelligence simulation of word processing.

Methods

Test Conditions

- Passage 417 words in length about history of Alaska displayed on CRT; each letter was 0.33 deg of visual angle; viewing distance (between reader and text) 48.3 cm (19 inches)
- Eye movements recorded using a limbic reflective technique (CRef. 1.904) with 1 msec sampling rate

Experimental Procedure

- Independent variable: word length (number of letters)
- Dependent variables: number of fixations per word, fixation probability per word
- Observer's task: with head held rigidly, read text one line at a time for comprehension; new line presented after button push
- 24 observers, college students

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Experimental Results

- The number of fixations per word increases as word length increases.
- Fixation probability increases as word length increases.
- Roughly 70% of function words and 25% of non-function words are not fixated.
- The function words *the* and *and* tend to be skipped more frequently than 18 other three-letter words tested (e.g., *but, had, for, not,* etc.) ($p < 0.001$).
- The probability that a given word will *not* be fixated when the word to the left of it was fixated decreases as word length increases.

Constraints

- Other factors such as text characteristics, as well as individual differences and reading skills, affect fixation duration (CRefs. 8.112, 8.113, 8.116). Most have not been investigated with regard to number of fixations and fixation probability.
- Not all studies find a tendency for fixations to skip function words more than non-function content words of equal length.

Key References

*1. Hogaboam, T. W., & McConkie, G. W. (1981). *The rocky road from eye fixations to comprehension* (Tech. Rep. No. 207). Champaign, IL: University of Illinois, Center for the Study of Reading.

Cross References

1.904 Methods of measuring eye movements;

8.111 Eye movements during reading: effect of viewing distance;

8.112 Eye movements during reading and reading speed: effect of school grade level;

8.113 Eye movements during reading: effect of "local" text characteristics;

8.115 Guidelines for determining which words are processed on a given fixation;

8.116 Influence of parafoveal (nonfixated) information during reading

8.115 Guidelines for Determining Which Words Are Processed on a Given Fixation

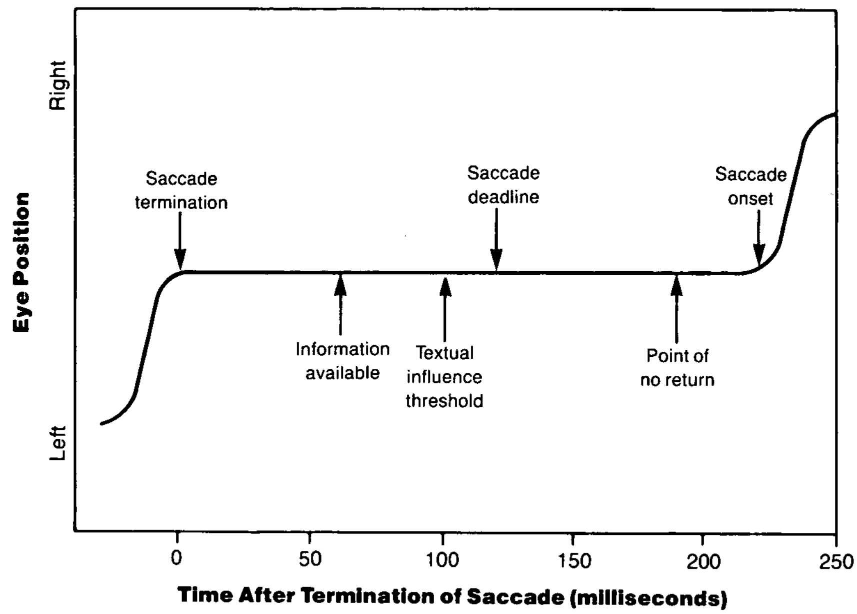

Figure 1. Critical times during the fixation period of reading. The curve represents relative eye position in a temporarily based eye movement record. (From Ref. 3)

Key Terms

Eye movements; reading; saccadic eye movements; visual fixation; word recognition

General Description

Being able to determine which words are processed during a given eye fixation would be invaluable in understanding the mechanics of reading. In idealized terms, we might view the fixating eye as a window. All words within the window are identified by the reader during that fixation, and integrated into the conceptual representation of the text. Then the eyes are programmed to move to a new area of text, with the length of this **saccade** determined so that a new word or set of words is brought into the window. However, this simple model encounters some problems.

1. Saccades (the abrupt jumps of the eyes between fixations) must be programmed by the visual system 100 msec before they are initiated (saccade deadline, Fig. 1); the saccade can be aborted up to 30 msec before onset (point of no return) but it cannot be modified (Ref. 2).

2. Because almost 100 msec are needed to begin to identify words, limited time is available for textual information from the current fixation to affect the duration of that fixation and the destination of the next saccade (Fig. 1; Ref. 2).

3. The window analogy is inappropriate for the processing of words. Rather, different window sizes must be assumed for different forms of information present in the word.

a. The shape, length, and first and last letters of a word up to 15 letter spaces (~5 deg) to the right of fixation can influence saccade length and subsequent fixation duration (CRef. 8.116).

b. Semantic information is available in a smaller window (up to six letter spaces to the right of fixation and four to the left or to the beginning of the word, whichever is less) (Ref. 2). It is not clear to what extent semantic information affects saccade length and fixation duration, though some effects have been demonstrated (CRef. 8.117). Table 1 presents guidelines for assigning word processing to particular fixations and for estimating total processing time for individual words. The constraints or cautions were adapted from Ref. 2.

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Applications

Interpretation of eye movement records; artificial intelligence simulation of word processing.

Constraints

- Fixation duration may not be the actual processing time for a given word.
- Saccade length is not based upon full use of information from the current fixation.
- Regressions (right-to-left eye movements) may be due to information gathered from more than the current fixation.
- Correlations among different properties of language can be misleading in interpreting the effects of language characteristics on reading (e.g., word length and word frequency are highly correlated, leading to ambiguous interpretation of length or frequency effects).
- Average measures may not reflect the range of individual abilities.
- The guidelines presented may be conservative and may underestimate the amount of processing per fixation, especially if the system processes redundantly to check itself.

Key References

1. Hogaboam, T. W., & McConkie, G. W. (1981). *The rocky road from eye fixations to comprehension* (Tech. Rep. No. 207). Champaign: University of Illinois, Center for the Study of Reading.

2. McConkie, G. W. (1983). *Eye movements and perception during reading: Perceptual and language processes* (pp. 65-96). New York: Academic Press.

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Cross References

8.111 Eye movements during reading: effect of viewing distance;

8.113 Eye movements during reading: effect of "local" text characteristics;

8.114 Eye movements during reading: effect of word length;

8.116 Influence of parafoveal (nonfixated) information during reading;

8.117 Factors affecting reading time for sentences

Table 1. Guidelines for determining which words are processed on a given fixation. (Adapted from Ref. 1)

If a word is fixated, it is read during that fixation
If a word is skipped, it was read during the fixation that preceded the forward saccade that skipped it
A word fixated immediately preceding a regressive (right-to-left) saccade is read during that fixation, but not the words skipped
If one word is read during a fixation, fixation duration is assigned to it
If two words or more are read during fixation, fixation time is divided equally among them
If a word is read on more than one fixation, the times are summed
All words to the right of fixation are assumed to be read later

8.116 Influence of Parafoveal (Non-Fixated) Information During Reading

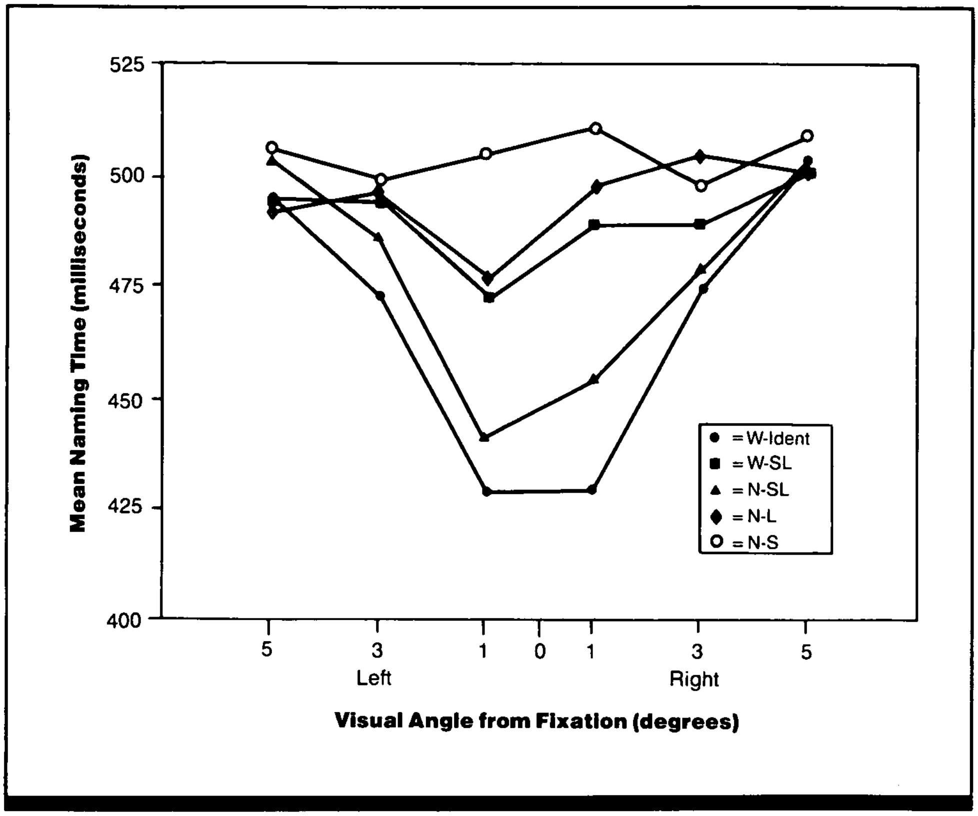

Figure 1. Effect of parafoveal preview on target naming. Preview letter string was presented at the distance from fixation shown on the horizontal axis. Five kinds of preview were used. W-ident: preview was same as target word (*chest, chest*); W-SL: preview was word with same shape and same first and last letters as target (*chart, chest*); N-SL preview was nonword with same shape and same first and last letters as target (*chovt, chest*); N-L: preview was nonword with same first and last letters as target (*chfbt, chest*); N-S: preview was nonword with same shape as target (*ckovf, chest*). Data shown are averages for 6 subjects. (From Ref. 3)

Key Terms

Eye movements; parafoveal preview; reading; saccadic eye movements; visual field location; visual fixation; word recognition

General Description

As we read, text falls on three areas of the **retina**: the fovea (a region of high visual acuity roughly 2 deg of visual angle in diameter and centered on the point of fixation), the parafovea (extending from the fovea out to ~6 deg from fixation), and the periphery (the area beyond the parafovea). Information in the foveal area of the retina has the greatest influence on reading. However, information from text yet to be read, lying to the right of fixation in parafoveal vision (for readers of English), also influences the mechanics of the reading process. The average duration of a fixation is ~200 msec, and the average length of a **saccade** (eye jump from one fixation point to another) is about eight letter spaces, but there is considerable variability around these mean values. Both values may be affected by information from the parafovea (which extends up to five or six deg or ~15 letter spaces to the right of fixation). Partly because of this influence, saccade length is not random. Fixations generally fall toward the centers of words, skip function words (*a*, *the*, etc.), and do not fall in blank spaces. This selectivity must be based upon parafoveal information because saccades must be programmed at least 100 msec before initiation and cannot be modified thereafter. In addition, the time needed to identify a briefly presented word is affected by information obtained in parafoveal preview, particularly information about the general shape and first and last letters of the word (Fig. 1). Semantic information from the periphery, however, appears to play little part in the reading process.

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The table lists several properties of words in parafoveal vision that affect eye movements during reading and performance on visual language tasks. One common experimental paradigm for assessing the effects of parafoveal preview is a word identification task. In such a task, observers generally fixate a point on a CRT display and a word or letter string is flashed in the visual parafovea or periphery. As the observer makes an instructed eye movement to the location where the letters appeared, the letter set at that location is replaced by a target word which the observer names. Latency to name the new word is measured. Figure 1 shows the results of such a study in which the parafoveal preview word was similar to the test word in overall word shape and/or first and last letters.

Applications

Diagnosis and training of poor readers; design of video displays; artificial intelligence simulation of processing words.

Constraints

• Methodological requirements of parafoveal preview experiments make the observer's task somewhat different from normal reading tasks.

• Under some experimental conditions, facilitation from parafoveal preview of word shape and first-last letters is not found (Refs. 2, 8).

• These factors may interact with information provided by text already read (Ref. 2).

Key References

1. Inhoff, A. W., & Rayner, K. (1980). Parafoveal word perception: A case against semantic preprocessing. *Perception & Psychophysics, 27,* 457-464.

2. McClelland, J. L., & O'Regan, K. (1981). Expectations increase the benefit derived from parafoveal visual information in reading. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 634-644.

3. McConkie, G. W. (1983). Eye movements and perception during reading. In K. Rayner (Ed.), *Eye movements in reading: Perceptual and language processes* (pp. 65-96). New York: Academic Press.

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8. Rayner, K., McConkie, G. W., & Zola, D. (1980). Integrating information across eye movements. *Cognitive Psychology, 12,* 206-226.

Cross References

8.111 Eye movements during reading: effect of viewing distance;

8.112 Eye movements during reading and reading speed: effect of school grade level;

8.113 Eye movements during reading: effect of "local" text characteristics;

8.114 Eye movements during reading: effect of word length

Table 1. Effect of parafoveal visual information on reading.

Property of Parafoveal or Peripheral Stimulus	Effect on Reading	Source
Word shape or initial and final letters	Parafoveal letter string decreases naming latency for target word provided it is the same as target word or has same shape and beginning and ending letters as target word, and is within ~15 letter spaces (5 deg) of fixation (Fig. 1)	Refs. 3, 5, 7
Word meaning	Meaning of parafoveal word affects perception of target word only if parafoveal word is within 1 deg of fixation	Refs. 1, 7
Word phonology	There is no difference in the facilitation of target word naming when the parafoveal preview begins with the same letter and the same phoneme as the target (*plane, prime*), and when the preview begins with the same letter but a different phoneme (*phone, prime*)	Ref. 8
Word length	Short words and function words (*the, and*) are more likely to be skipped (not fixated) in reading than longer words	Ref. 4 CRef. 8.114
Spaces between words	Fixation seldom falls on blank spaces When spaces are filled with asterisks, reading is severely impaired	Refs. 3, 6

8.117 Factors Affecting Reading Time for Sentences

Table 1. Factors affecting reading time for sentences.

Factor	Effect on Reading Time	Source
Type of text (e.g., narratives versus textbook)	In a study using texts that varied in many characteristics, type of text was the single most important determinant of reading speed, accounting for 33% of variance in reading speed	Ref. 5
Number of words	Second most significant determinant of reading speed (after type of text), accounting for 9.4% of variance	Ref. 5
Number of propositions in sentence	Effect on reading speed was small, accounting for 1.8% of variance, in study comparing it with other factors. Study looking specifically at effect of propositional structure found incremental reading time of 1 sec per proposition	Refs. 5, 6 CRef. 8.118
Ordering of information in sentence	In reading instructions on the operation of electronics devices, reading speed increases when sentence ordering follows temporal order of events and when action precedes its consequence	Refs. 3, 4 CRef. 8.123
Concurrent task	For unpracticed observers, performance of concurrent dictation slows reading performance, but decrement in reading performance virtually disappears with extended practice	CRef. 8.120
Purpose of reading	Observers reading for subsequent recall read more slowly than those reading for subsequent recognition test	Ref. 1 CRef. 8.119
Method of presentation	Under some conditions, sentences can be read 2-3 times faster when words (or small groups of words) are presented sequentially in the same spatial location (so that no eye movements are required) than when they are presented conventionally as a horizontal string of words	CRef. 8.121

Key Terms

Readability; reading speed; sentence perception; text engineering

General Description

The speed with which sentences are read is affected by many factors, including the purpose in reading, length and construction of sentences, type of material read, the length and familiarity of individual words, and reading skill. The table summarizes the effects of such factors on reading time.

Applications

The design of documents and textual materials to improve readability and comprehension.

Constraints

- Magnitude of comparative effects of various factors as studied in Ref. 5 depends to some extent upon the range of the factors manipulated.
- In many experiments, the conditions of text presentation differ from those of natural reading. For example, in Ref. 1 subjects pressed a button to see each new word so that word-by-word reading times could be measured.

Key References

1. Aaronson, D., & Scarborough, H. (1977). Performance theories for sentence coding: Some quantitative models. *Journal of Verbal Learning and Verbal Behavior, 16,* 277-304.

2. Carr, T. (1986). Perceiving visual language. In K. R. Boff, L. Kaufman, & J. P. Thomas, (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes & performance.* New York: Wiley.

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6. Kintsch, W., & Keenan, J. (1973). Reading rate and retention as a function of the number of propositions in the base structure of sentences. *Cognitive Psychology, 5,* 257-274.

Cross References

8.118 Reading speed: effect of semantic structure;

8.119 Reading speed: effect of reading task (comprehension or recall);

8.120 Reading speed and accuracy: effect of performing a concurrent task;

8.121 Text reading speed and accuracy with rapid sequential presentation of text;

8.123 Reading speed and text memory: effect of information ordering

8.118 Reading Speed: Effect of Semantic Structure

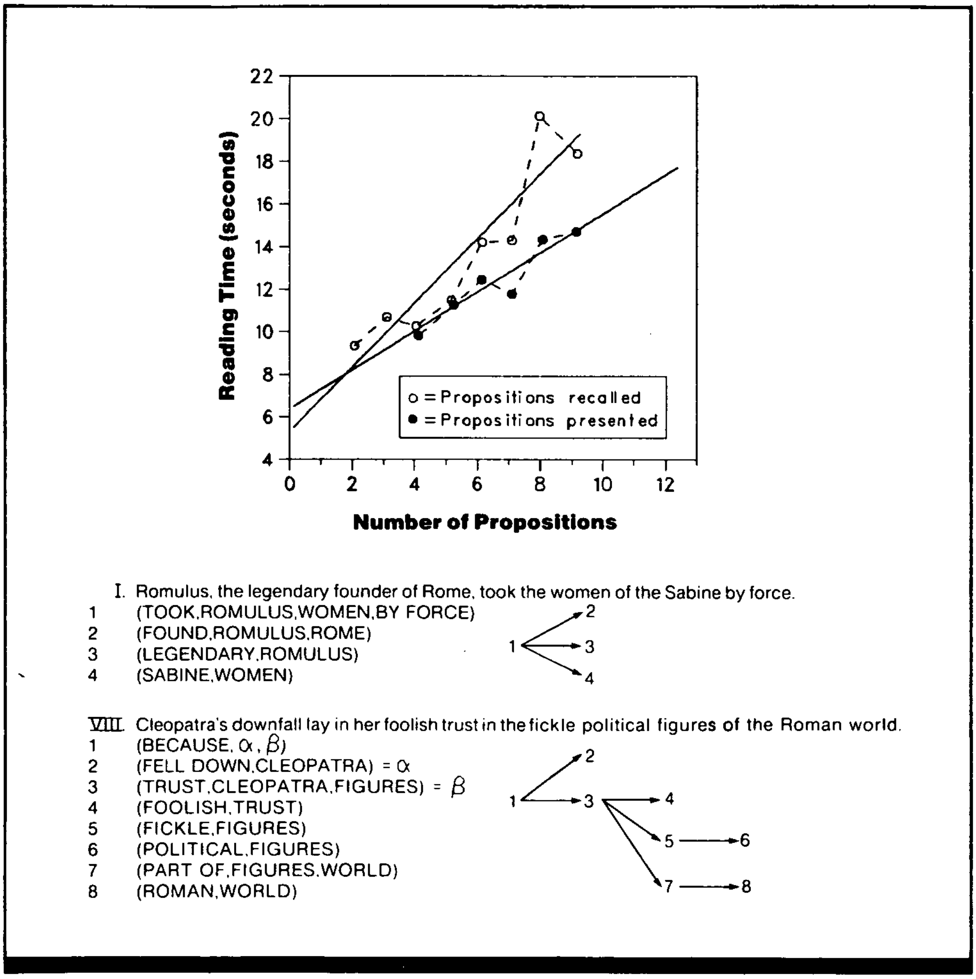

Figure 1. Mean reading time for sentences as a function of the number of propositions in the sentences actually presented and the number of propositions from the sentences that were recalled. Solid lines are least-squares fit showing a linear relationship between the number of propositions and reading time. Lower portion of figure illustrates propositional analysis of two sample sentences used in the study. (From Ref. 1)

Key Terms

Readability; reading speed; sentence recall; sentence structure; text engineering

General Description

When the number of words in a sentence is held constant, reading time increases as the number of propositions, or ideas, contained in the sentence increases. This relationship holds regardless of whether one counts propositions that are read or only ones that are remembered.

Applications

The design of documents and textual materials to improve readability and comprehension.

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Methods

Test Conditions

- 10 unrelated sentences 14-17 words long dealing with an unfamiliar topic (classical history)
- Number of separate ideas (propositions) upon which each sentence is based varied between 4 and 9
- Sentences presented on slides on screen 3 m in front of subject

Experimental Procedure

- Independent variable: number of propositions contained in sentence or recalled
- Dependent variable: reading time
- Observer's task: press button after reading each sentence to clear screen; write sentence just seen
- Instructions to observers emphasized that exact wording was not as important as meaning of sentences and that amount remembered was more important than speed
- 29 college students, unpracticed

Experimental Results

- Reading time increases as the number of propositions in a sentence increases; for sentences with an equal number of words, observers require an extra 1 sec of reading time per proposition.
- Relationship between reading time and number of propositions is even more pronounced when the number of propositions recalled is measured rather than the number of propositions in the sentence; observers require an additional 1.5 sec reading time for each proposition recalled.

Variability

Scoring of recalled propositions was done independently by two investigators who agreed in 95.2% of all recall protocols.

Constraints

- Particular types of propositions and structural relations among propositions may interact with number of propositions in their effects on reading time.
- It is not always possible to determine unambiguously the number of different propositions in a sentence; different text grammar systems may parse the same sentence into different numbers of propositions.
- Many factors (such as type of text, number of words, and information ordering) affect reading time for sentences and should be considered in applying these data under different conditions (CRef. 8.117).

Key References

*1. Kintsch, W., & Keenan, J. (1973). Reading rate and retention as a function of the number of propositions in the base structure of sentences. *Cognitive Psychology, 5*, 257-274.

2. Kintsch, W., & van Dijk, T. A. (1978). Toward a model of text comprehension and production. *Psychological Review, 85*, 363-394.

Cross References

8.117 Factors affecting reading time for sentences;

8.123 Reading speed and text memory: effect of information ordering;

8.124 Sentence comprehension: effect of syntactic structure;

Handbook of perception and human performance, Ch. 29, Sect 6.3

8.119 Reading Speed: Effect of Reading Task (Comprehension or Recall)

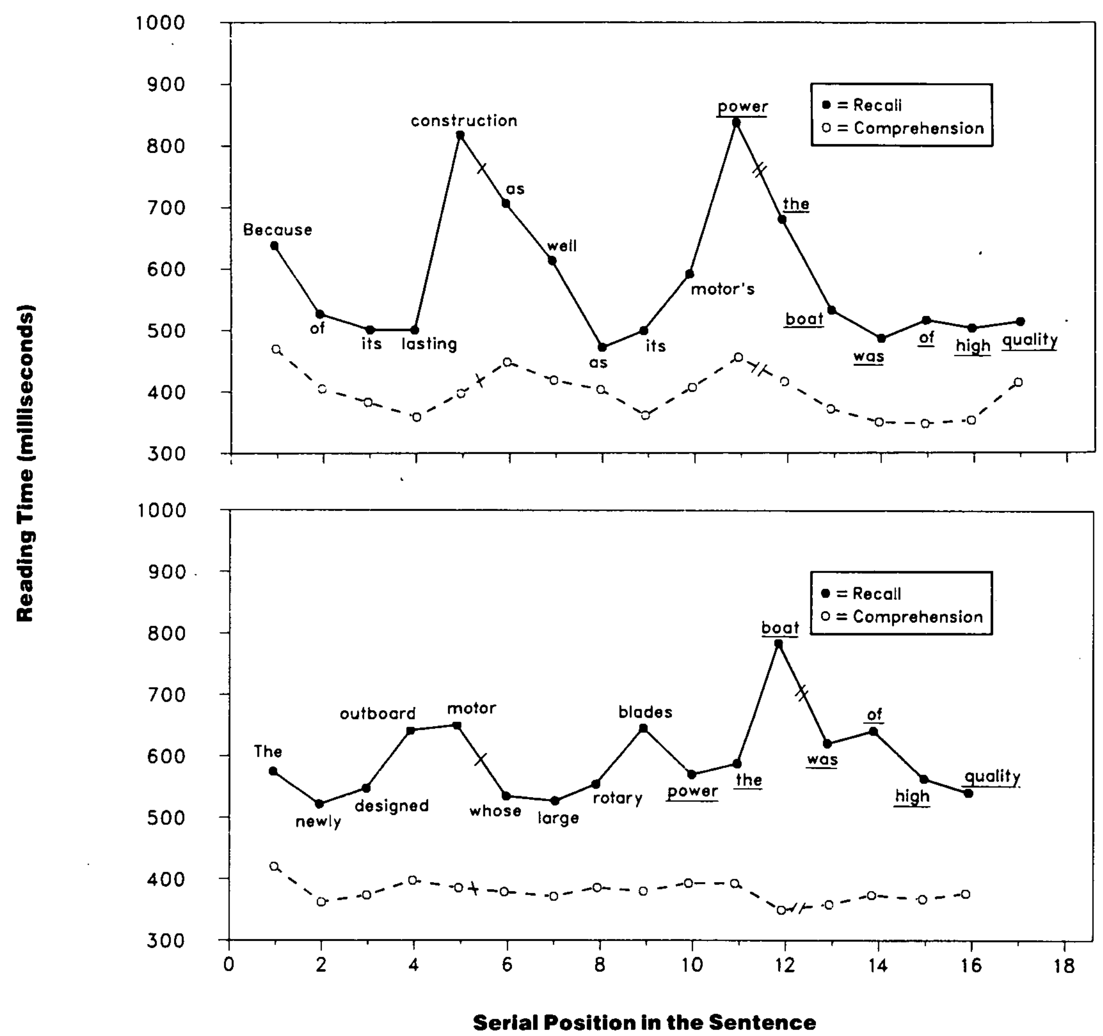

Figure 1. Word-by-word reading times for two sample sentences, averaged for the recall and comprehension groups. The short single or double line markers on the graphs indicate natural breaks between major phrases or clauses in the sentences, as judged by 20-30% (single line) and 40-80% (double line) of naive subjects not participating in the main experiment. (From Ref. 3)

Key Terms

Chunking; reading speed; sentence recall; text comprehension

General Description

Reading for comprehension leads to different patterns of word-by-word reading time than reading for recall. This indicates that these two tasks may involve different coding strategies (see Ref. 1 for a review). Word reading times are longer when sentences are read for recall than when they are read for comprehension. In addition, word reading times are more uniform across sentences read for comprehension, but prolonged pauses in word reading occur when recall is required. These pauses occur almost exclusively at the boundaries between major constituents of a sentence, such as grammatical clauses.

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Applications

Situations requiring rapid presentation and comprehension or verbatim memory of written material; diagnosis and training of poor readers; artificial intelligence simulation of word processing.

Methods

Test Conditions

- 90 sentences presented one word at a time on CRT; presentation under observer's control; words presented centrally 0.61 m from observer
- Letters 1.27 cm high, 0.85 cm wide; all uppercase
- Sentences varied from 9-19 words (mean, 14.4 words); no punctuation marks
- Six practice trials and 90 test trials per observer

Experimental Procedure

- Independent variable: type of task following reading (comprehension or recall), number of words in sentence, position of given word in sentence
- Dependent variable: reading time for each word in msec, measured by latency of button press to present next word
- Observer's task: for comprehension condition, answer yes/no question about sentence just read; for recall condition, write down entire sentence verbatim after reading
- Cash payoffs contingent on speed and accuracy
- 24 unpracticed undergraduate observers for each task condition

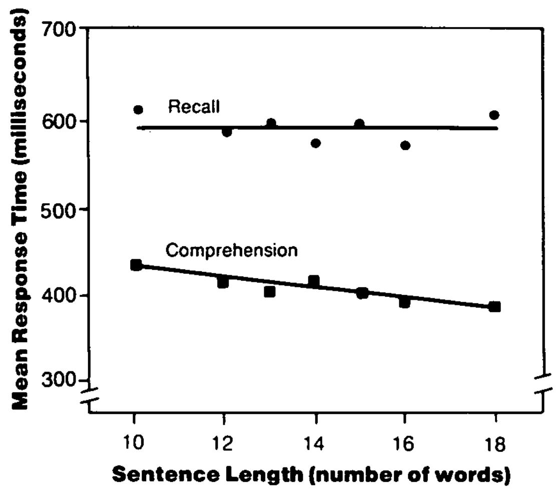

Figure 2. Mean reading time, averaged over all words in the sentence, for sentences of various lengths for recall and comprehension tasks. (From Ref. 2)

Experimental Results

- Word reading times are longer when sentences are read for recall than when they are read for comprehension ($p < 0.0005$).
- Practice markedly reduces word reading times with both comprehension and recall task ($p < 0.0005$), although practice effect is greater for comprehension ($p < 0.05$).
- Peaks in the distribution of reading time are evident across sentences read for recall (where a peak is defined as reading time >5% longer than the mean reading time for the two immediately adjacent words). These peaks occur at the breaks between major phrases or clauses in sentences, at a word either just before or just after the break.
- Pauses in reading at phrase boundaries when verbatim recall is required show that words are "chunked" in short-term memory according to the phrasing of the sentence.
- Reading time for individual words decreases with sentence length for the comprehension condition ($p < 0.005$) but not for the recall condition (Fig. 2).

Variability

Significance of independent variables and interactions determined by analysis of variance.

Repeatability/Comparison with Other Studies

Results are consistent with those of other studies.

Constraints

- Peaks in distribution of reading time at phrase boundaries across sentences read to recall are greater for slower than for faster readers.
- Many factors (such as type of text, number of words, and information ordering) affect reading time for sentences and should be considered in applying these data under different conditions (CRef. 8.117).
- The serial (word by word) presentation method used differs from normal reading conditions.

Key References

1. Aaronson, D. (1976). Performance theories for sentence coding: Some qualitative evidence. *Journal of Experimental Psychology: Human Perception and Performance, 2*, 42-55.

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Cross References

8.117 Factors affecting reading time for sentences;

8.121 Text reading speed and accuracy with rapid sequential presentation of text;

8.122 Reading speed and accuracy with sequential versus simultaneous presentation of text;

Handbook of perception and human performance, Ch. 29, Sect. 6.3

8.120 Reading Speed and Accuracy: Effect of Performing a Concurrent Task

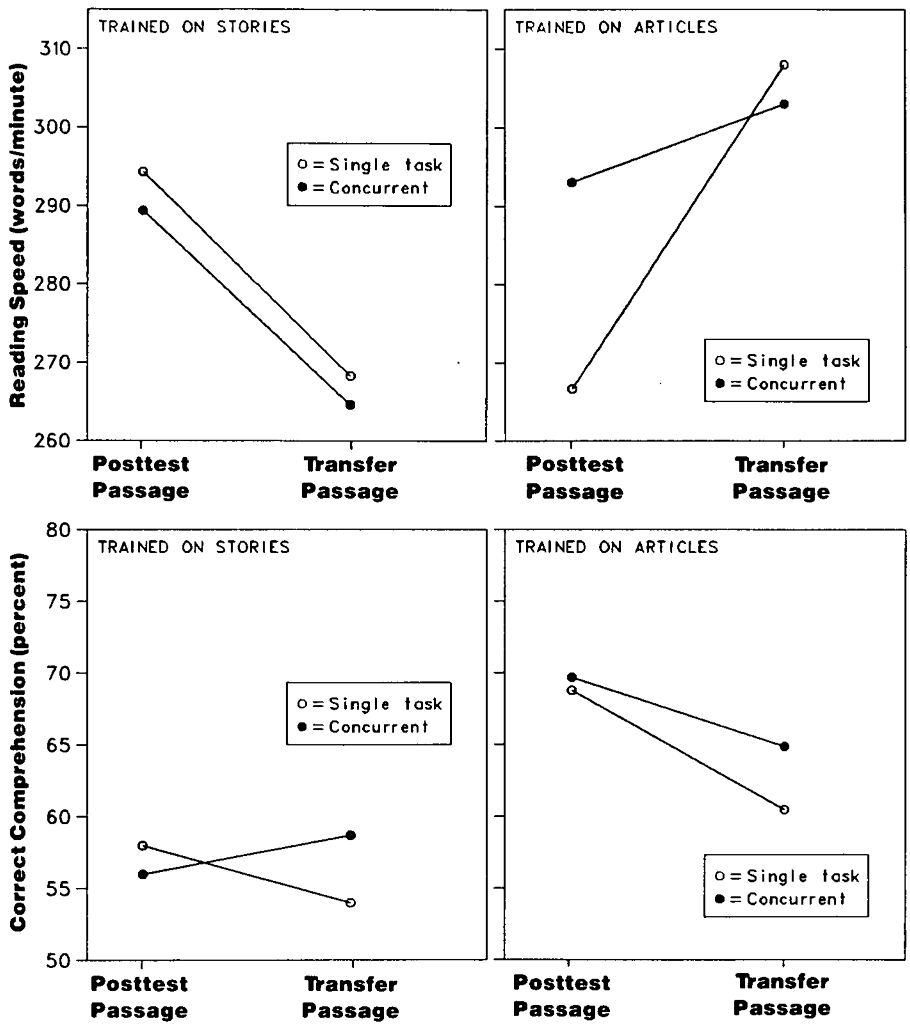

Figure 1. Mean reading speed and comprehension scores when reading only (single task) and when simultaneously taking dictation (concurrent task). Observers trained on stories read stories as the posttest passage after training and encyclopedia articles during transfer testing; observers trained on articles read articles during posttest and stories during transfer testing. Plots show changes in speed and comprehension during transfer for different types of passages, but no significant decrement while simultaneously taking dictation relative to reading alone. (From *Handbook of perception and human performance*, based on data from Ref. 1)

Key Terms

Concurrent task; divided attention, interference; practice; reading speed; text comprehension; text engineering; transfer of training

General Description

With practice, people learn to write from dictation while reading with no loss of speed or comprehension. Taking dictation while simultaneously reading prose passages is initially extremely difficult, but after training observers can perform the tasks simultaneously as well as they can perform each task separately in terms of accuracy and speed. Training transfers to more difficult reading material, though transfer is not as complete as with a shift to easier material.

Applications

Organization of complex tasks and training programs in such tasks.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Reading materials: short stories or encyclopedia articles from *Encyclopedia Britannica* and *International Encyclopedia of the Social Sciences*, ranging from 700-2,500 words
- Short stories were highly redundant; encyclopedia articles less redundant
- Comprehension questions were "loose" (looking at general points) or "strict" (direction to a specific detail)
- Dictation material was list of words randomly selected from established norms (Ref. 2); dictation rate 10.2-10.3 words/minute
- Four stages: pretest, training, testing, and transfer; one hour-long session/day, 5 days/wk, for 14 wks
- Three days of pretesting: subjects read two stories and two encyclopedia entries followed by loose comprehension tests, then two of each followed by strict comprehension tests, then practiced taking dictation from two 40-word lists
- Training averaged 35-40 days; each day consisted of one control trial (no dictation), followed by two experimental trials (with concurrent dictation); training ended when each observer's reading performance on control (no dictation) and experimental (concurrent dictation) trials were nearly equal in terms of reading speed (within 15 words/min) and comprehension (scores within 5% of each other), based on 5-day average
- Testing stage followed training immediately and consisted of 5 days of control and experimental trials followed by strict comprehension task
- Transfer stage identical to testing stage but subject transferred to other type of reading material

Experimental Procedure

- Independent variables: concurrent dictation (presence or absence), level of difficulty of reading material in training and transfer (stories or encyclopedia articles), type of comprehension test (loose or strict)
- Dependent variables: reading speed, reading comprehension
- Subject's task: read assigned material with or without concurrent dictation task, complete written comprehension test
- 7 subjects, all undergraduates, 4 trained with stories and read encyclopedia entries in transfer testing, 3 trained with encyclopedia entries and read stories during transfer testing

Experimental Results

- After sufficient training, all observers are able to perform a dictation task while reading with no loss of reading speed or comprehension. Observers who train in reading stories while taking dictation require an average of 38 hr of training to reach the point where the dictation task does not interfere with reading; observers who train with encyclopedia entries require an average of 43 hr of training.
- After training, 6 of 7 observers show immediate transfer (i.e., no loss of reading speed or comprehension with a concurrent dictation task) when the type of reading material is changed from stories to encyclopedia articles, or vice versa. One subject showed a decline in reading speed when transferred from stories to encyclopedia entries and required 8 days of further training on encyclopedia entries to read this material as rapidly with and without the concurrent dictation task.

Variability

The observers in the study began with markedly different reading speeds and levels of comprehension.

Repeatability/Comparison with Other Studies

Similar results obtained for 2 subjects in an earlier study (Ref. 3).

Constraints

- Dual-task performance after training has been tested with only a very limited number of tasks.
- There is considerable interference between tasks in the early stages of training.
- Many factors (such as type of text, number of words, and information ordering) affect reading time for sentences and should be considered in applying these data under different conditions (CRef. 8.117).

Key References

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3. Spelke, E. S., Hirst, W. C., & Neisser, U. (1967). Skills of divided attention. *Cognition, 4*, 215-230.

Cross References

7.216 Auditory divided attention: effect of practice;

7.718 Use of the subsidiary task paradigm in workload assessment;

8.117 Factors affecting reading time for sentences;

Handbook of perception and human performance, Ch. 29, Sect 6.4.

8.121 Text Reading Speed and Accuracy with Rapid Sequential Presentation of Text

Key Terms

Communications; rapid communication display; rapid serial visual presentation; reading speed; sentence perception; text perception

General Description

Readers can comprehend brief messages presented at very high rates when small text segments (e.g., single words) appear in temporal succession at a single spatial location, such as a window on a video monitor. This display method, called rapid serial visual presentation (RSVP), permits reading without eye movements.

With RSVP, sentences can be read at rates as high as 8-12 words per second. This is ~2-3 times the rate normally adopted by skilled readers with conventional text. At rates higher than 12 words per second, visual factors such as masking prevent clear perception of the text.

Readers can also comprehend paragraphs displayed in this way. However, retention is poor at very high rates. When brief pauses are inserted between sentences and display rates are moderate, RSVP performance is approximately comparable to performance with conventional text under time-limited or "skimming" conditions.

Over a variety of presentation rates, comprehension for RSVP paragraphs is best with text windows that average 12 character spaces in length and present short "idea units" rather than single words in each window. RSVP paragraph reading is degraded when parafoveal information is provided.

Table 1 summarizes several experimental studies on RSVP sentence and paragraph reading.

Applications

• Design of computerized displays for presenting brief messages; design of an alternative to "Times Square" displays for news bulletins and advertising; design of computerized remedial reading programs; design of reading aids for people with impaired peripheral vision.

Constraints

• At rates greater than 12 words per second, satisfactory reading is prevented by visual factors such as masking. Practical rates are below this upper limit and depend on the type of text.

• Hardware and software capabilities must permit rapid updates of the display window, and rate of display update must be under program control.

• With RSVP, readers cannot save time by skipping over unimportant text.

Key References

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4. Juola, J., Ward, N., & McNamara, T. (1982). Visual search and reading of rapid serial presentations of letter strings, words, and text. *Journal of Experimental Psychology: General, 111*, 208-227.

5. Masson, M. (1983). Conceptual processing of text during skimming and rapid sequential reading. *Memory and Cognition, 11*, 262-274.

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Cross References

8.119 Reading speed: effect of reading task (comprehension or recall);

8.122 Reading speed and accuracy with sequential versus simultaneous presentation of text;

Handbook of perception and human performance, Ch. 29, Sect. 3.2.

Table 1. Effect of presentation rate on sentence and paragraph reading with rapid serial visual presentation.

Type Text	Presentation Method	Rate (words/sec)	Performance Measure	Results	Source
Sentences 6 words	1 word per frame	16	Exact recall with correct word sequence	3.09-4.41 words per sentence recalled depending on sentence complexity	Ref. 3
Sentences 8-14 words	1 word per frame	12	Sentence plausibility judgment	11% errors	Ref. 7
			Recall	87% correct recall	
Sentences 9 words	1 word per frame	10, 20	Letter search	82% found at 10 words/sec; 64% at 20 words/sec	Ref. 4
			Category search (find words belonging to given category)	91% found at 10 words/sec; 79% at 20 words/sec	
Specially prepared paragraphs 17-128 words	1 word per frame	4, 8, 12	Report topic of paragraph	90% correct at all rates	Ref. 7
			Verbatim and paragraph recall	Correct recall of 20-37% of idea units, depending on rate	
				Similar performance for rapid serial visual presentation and conventional reading (skimming)	
Paragraphs from standard reading tests	Chunks of 5, 10, or 15 characters per frame (1-3 words per chunk)	5.7, 8.6	Four-alternative multiple-choice questions	48-65% correct depending on rate, frame size, type of paragraph	Ref.4
				Similar performance for RSVP and paced conventional reading (skimming)	
Paragraphs from *Reader's Digest*	1 word per frame	6.25-11.67	Answer questions, state topic	RSVP performance inferior to skimming	Ref. 5
Paragraphs from standard reading tests	Chunks of 1 word per frame to 20 characters per frame (3-4 words)	3.33, 13.3	Four-alternative multiple-choice questions	Percent correct depends on type text, presentation method, and rate	Ref. 2
				Optimal results with short idea segments, ~12 characters	
				Similar performance for RSVP and paced conventional reading (skimming)	
Paragraphs from standard reading tests	Chunks of 5, 8, or 12 characters per frame	4.2, 8.3	Four-alternative multiple-choice questions	Percent correct depends on rate, frame size, observer ability, presentation format	Ref. 1
				Performance degraded when parafoveal information is present	

Note: For conventional text presentation, a skilled reading rate of 4-5 words/sec can be assumed for comparison purposes.

8.122 Reading Speed and Accuracy with Sequential Versus Simultaneous Presentation of Text

Key Terms

Letter recall; letter recognition; rapid communication display; rapid serial visual presentation; reading speed

General Description

Presenting three digits sequentially in the same CRT window rather than using separate windows and simultaneous presentation reduces the amount of time necessary to perceive and memorize the digits (Fig. 1). The time reduction in the serial display is due to elimination of the time needed for programming and executing saccadic eye movements.

Applications

Design of computerized displays when space and/or time considerations are critical (e.g., status indicators in aircrew stations or in nuclear power control rooms).

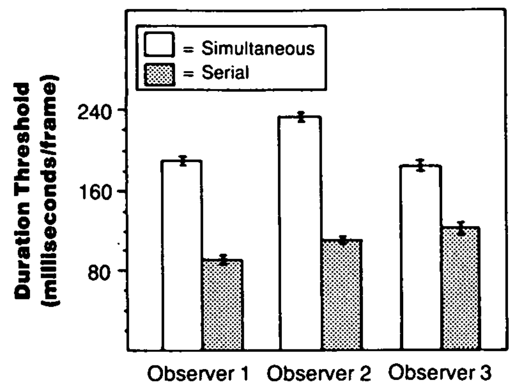

Figure 1. Duration threshold for 90% correct recall of digit triads as a function of display method (simultaneous versus serial presentation). (From Ref. 1)

Methods

Test Conditions

- Simultaneous condition: randomly selected digits appeared in three fixed windows centered on a CRT screen and located to form the corners of an equilateral triangle with each side 11 deg of visual angle in length
- Serial (sequential) condition: randomly selected digits presented in temporal sequence at one window
- Frame duration for the serial condition ranged from 260-60 msec, decreasing by 20 msec per step; five trials at each duration during a block of 55 trials; identical average durations for the simultaneous condition but all frames appeared and disappeared simultaneously with total exposure duration three times the frame duration
- High-resolution display (640 x 350); amber P134 phosphor; positive contrast (luminous letters on a darker background); dim background luminance (0.27 cd/m^2)
- Viewing distance was 63.5 cm; each digit was 0.25 deg wide

Experimental Procedure

- Independent variables: display condition, frame duration
- Dependent variable: duration threshold, defined as duration per frame for correct recall of all digits on 90% of trials, interpolated from raw data (percent correct versus frame duration functions)
- Observer's task: type the three digits in order of presentation for the serial condition or in fixed window sequence for the simultaneous condition (upper window, lower left window, lower right window); feedback provided
- 3 observers; 1 and 2 highly practiced with both display conditions; observer 3 familiarized with task prior to data collection

Experimental Results

- Duration thresholds for digit triads were significantly shorter with rapid serial presentation than with simultaneous presentation ($p < 0.001$).
- Duration thresholds for three simultaneously presented digits were 175.4 msec/frame, 233.7 msec/frame, and 186.2 msec/frame for observers 1, 2, and 3, respectively.
- Duration thresholds with the serial presentation of the digits were 89.3 msec/frame, 107.9 msec/frame, and 123.5 msec/frame for observers 1, 2, and 3, respectively.

Variability

The standard error bars in Fig. 1 represent standard errors of the mean duration threshold averaged across three replications. *t* test for correlated pairs used to test for differences between serial and simultaneous presentation.

Constraints

- Hardware and software capabilities must permit rapid update of the display window for serial displays, and rate of display update must be under program control.

Key References

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Cross References

8.119 Reading speed: effect of reading task (comprehension or recall);

8.121 Text reading speed and accuracy with rapid sequential presentation of text

8.123 Reading Speed and Text Memory: Effect of Information Ordering

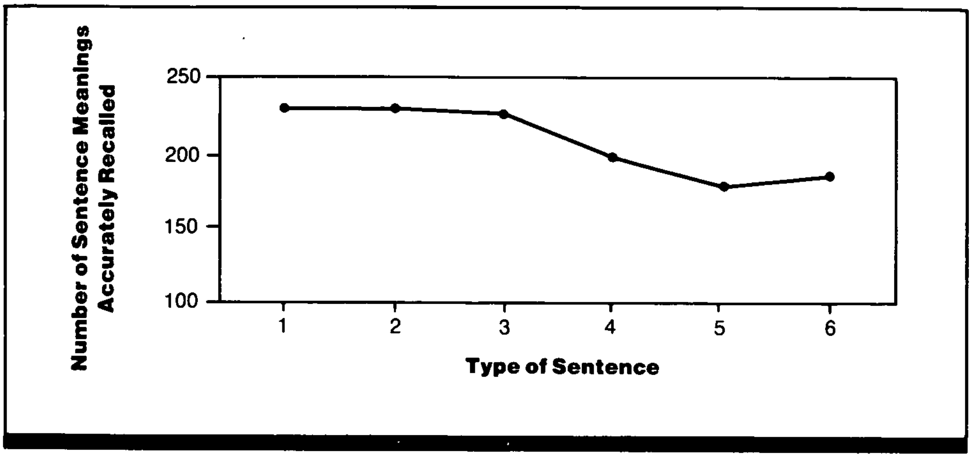

Figure 1. Recall of sentences as a function of sentence type (whether sentence order of events agrees with temporal order) (Study 1). Sentence types are described in Table 1. For types 1-3, sentence event order agreed with temporal order; for types 4-6, sentence event order disagreed with temporal order. (Based on data from Ref. 2)

Key Terms

Reading speed; sentence perception; sentence recall; sentence structure; text engineering

General Description

Sentences are recalled more accurately when the order of events in the sentences agrees with the temporal order of events. In addition, when sentences convey instructions to be followed, reading times are faster for sentences in which the action to be performed is described before the consequence of the action.

Applications

Design of documents and textual materials to improve readability and comprehension.

Methods

Test Conditions

Study 1 (Ref. 2)

- Seventy-two sets of six sentences contained two clauses each: in half, sentence order of events agreed with temporal order of events (Table 1, sentence types 1-3); in the other half, event order and temporal order disagreed (Table 1, sentence types 4-6)
- Noun cue (subject common to a six-sentence set) presented with each sentence
- Observer studied each sentence and noun cue for 10 sec; completed trial by recalling each sentence consecutively, from its noun cue
- Six sentences per trial, 12 trials per observer

Study 2 (Ref. 4)

- Sentences gave directions for operating a panel consisting of rotating knobs controlling meters
- Each sentence contained two clauses, one designating the knob to be returned (action) and the other designating the meter reading to be achieved (consequence)
- In half of sentences, first clause described the action and the second the consequence; in the other half, the order was reversed
- Observer studied each of four sentences at own pace, performing task immediately after studying each (immediate performance) or after seeing all four sentences (delayed performance)
- Three trials per condition per observer

Table 1. Types of sentences used in Study 1. (From Ref. 2)

1. S_1 before S_2: He tooted the horn before he swiped the cabbages.
2. S_1 and then S_2: He tooted the horn and then he swiped the cabbages.
3. AfterS_1 S_2: After he tooted the horn he swiped the cabbages.
4. S_2 after S_1: He swiped the cabbages after he tooted the horn.
5. S_2 but first S_1: He swiped the cabbages but first he tooted the horn.
6. Before S_2 S_1: Before he swiped the cabbages he tooted the horn.

Types 1-3 represent sentences in which the order of events as written agrees with the temporal order of events; types 4-6 represent sentences in which the order of events presented in the sentence does not agree with the temporal order. An example of each sentence type is given.

Experimental Procedure

- Repeated measures design
- Independent variables: order of clauses in sentence (Study 1), performance condition (immediate or delayed) (Study 2)
- Dependent variable: number of sentences accurately recalled (Study 1), reading time for each sentence (Study 2)
- Observer's task: recall sentence from noun cue (Study 1); read and perform instructions displayed on CRT (Study 2)
- 24 observers (Study 2); 20 observers (Study 2)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Verbatim consecutive recall of sentences in which event order and temporal order agree is more accurate than recall of sentences in which they disagree. The underlying sense or gist of same-order sentences is also recalled more frequently ($p < 0.001$).
- Sentences conveying instructional material are read more quickly when the action to be performed is presented before its consequence than when information is presented in the reverse order ($p < 0.05$). This is true both when the action is carried out immediately after a single instruction and when it is carried out after a more extended sequence of instructions.
- The advantage in reading time for sentences in which the action to be performed is presented first and its consequence second is greater when the consequence occurs in the main clause of the sentence.
- In Study 2, error rate for immediate performance was 2.0% compared to 16.7% for delayed (memory) performance ($p < 0.01$).

Variability

Significance of immediate versus delayed performance differences (Study 2) was assessed by paired *t* test; for other conditions in both studies, significance determined by analysis of variance.

Constraints

- Many factors (such as type of text, number of words, and information ordering) affect reading time for sentences and should be considered in applying these data under different conditions (CRef. 8.117).
- Results are likely to be influenced by the level of reading skill.

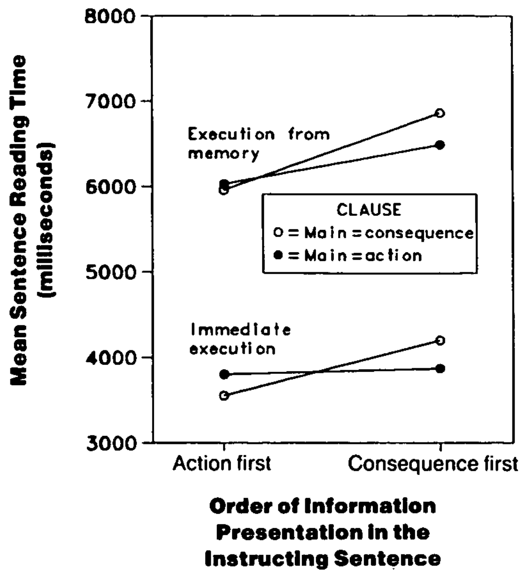

Figure 2. Mean reading time for sentences presenting instructions for operating a simple electronic device (Study 2). Each sentence presented an action to be carried out on a knob and the resulting meter reading (consequences of the action). Either the action or the consequence could appear first in the sentence and either the action or the consequence was described in the main clause of the sentence. Observers executed the instruction given in the sentence immediately or after a set of four different instructions had been read. (From *Handbook of perception and human performance*, adapted from Ref. 4)

Key References

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Cross References

8.117 Factors affecting reading time for sentences;

8.118 Reading speed: effect of semantic structure;

8.124 Sentence comprehension: effect of syntactic structure;

8.125 Memory for inferences made during text reading;

Handbook of perception and human performance, Ch. 29, Sect 6.3

8.124 Sentence Comprehension: Effect of Syntactic Structure

Key Terms

Reading; sentence structure; text comprehension; text engineering

General Description

Sentence comprehension is influenced by syntactic structure. The influence of syntax is investigated through paradigms which measure the speed and accuracy with which observers can answer questions after reading a story, can complete or recall a sentence, can verify the truth or falsity of a sentence, can carry out a command, can break down a sentence into component clauses, can compare pictures to sentences, or can judge the semantic reasonableness of a sentence. The accompanying table summarizes the effects of several syntactic characteristics on sentence comprehension.

Applications

Design of documents and other textual materials to improve readability and comprehension; artificial intelligence simulation of word processing.

Constraints

- Results are likely to be influenced by reading skill level.

Table 1. Effects of syntactic characteristics on sentence comprehension.

Factor	Effect on Comprehension	Source
Relative pronouns	Comprehension is better when all relative pronouns (e.g., *that, which, whom*) signaling the beginning of a phrase are included than when they are not included	Ref. 3
Highlighting of phrase structure	Highlighting *phrases* in sentences by adding extra space between appropriate words improves comprehension for readers with adequate vocabulary but poor comprehension	Ref. 2
Nesting of clauses (embedding between the subject and predicate of the main clause and successive clauses)	Sentences in which clauses are nested (e.g., "The dog that the cat that the bird fought scolded approached the colt") and in which understanding the syntax is necessary to understand sentence's meaning are very difficult to comprehend; comprehension improves when observers hear a paraphrase of the meaning of such sentences	Ref. 9
Location of subordinate clauses	When successive clauses are added to the left of the main clause in a sentence (e.g., "The electricity-powered toe-chomping rock-throwing lawn mower ran over its own cord"), comprehension is better than when clauses are nested or added to the right of the main clause	Ref. 7
Negation	In completing a statement and in verifying a sentence, responses are faster and more accurate for affirmative than for negative sentences	Ref. 10
	Sentences containing the qualifying negative *except* are harder to comprehend than are equivalent positive sentences	Ref. 4
	In comparing sentences to pictures, people respond more slowly to sentences which include negatives than to those which do not; this is true both for positive and negative matches, regardless of the order of presentation of the sentence and picture	Ref. 1
	Sentence verification time is faster and recall more accurate for affirmative than for negative sentences; sentences with negatives in the predicate (e.g., "It's true that a villian isn't kind") are verified faster when true than when false, but sentences with denials (e.g., "It isn't true that a rocket is slow") are verified faster when false	Ref. 5
	For sentences with multiple negatives, the most dramatic reduction in comprehension occurs with three or more negatives	Ref. 8

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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9. Stolz, W. (1967). A study of the ability to decode grammatically novel sentences. *Journal of Verbal Learning and Verbal Behavior, 6,* 867-873.

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Cross References

8.118 Reading speed: effect of semantic structure;

8.123 Reading speed and text memory: effect of information ordering;

8.128 Schema theory of memory for text

8.125 Memory for Inferences Made During Text Reading

Key Terms

Reading; text comprehension; text recall

General Description

Experiments on reading comprehension and memory for text demonstrate that readers whose purpose is text comprehension actively create an abstract rather than a literal representation of the text as they read. At any given point, material already read is used as a context in which to interpret upcoming material. As a result, readers actively make inferences from the text while reading; they quickly forget much of the literal wording of the text and remember the meaning. Readers include information that was implied but not explicitly stated in recalling the text (Ref. 1), and they falsely recognize true inferences as statements they previously read (Fig. 1).

Applications

Design of documentation and textual materials to improve readability, comprehension, and retention.

Methods

Test Conditions

- Twenty short stories (stories for control versus experimental groups differed in terms of instrument of action or a probable consequence) and 38 recognition questions
- Test sentences included two filler items, 12 sentences identical to story sentences, 12 sentences using elements from the story in a way inconsistent with the story, 12 sentences not identical to story sentences but true by implication for experimental, but not control, stories
- Stories read sequentially with 2-sec delay between stories; subject instructed to listen carefully; 3 min later test sentences were read at 10-sec rate; subject indicated "yes" on an answer sheet if sentence was exactly the same as sentence in original story

Experimental Procedure

- Yes/no recognition procedure
- Independent variables: experimental versus control stories, type of recognition sentence
- Dependent variable: number of "yes" responses
- Subject's task: say whether test sentence was verbatim from story
- 40 undergraduate subjects

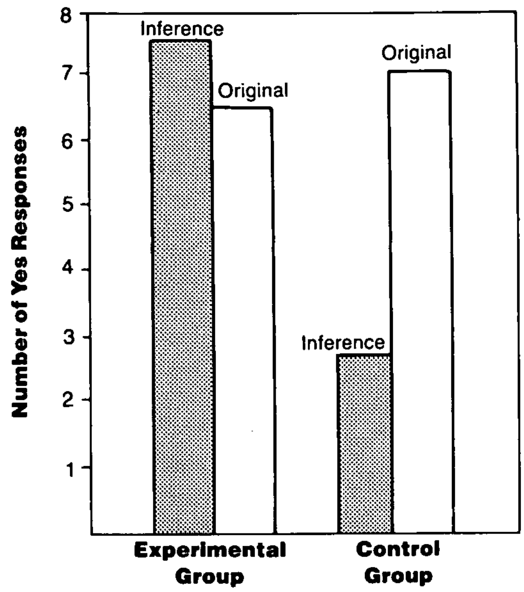

Figure 1. Mean number of "yes" responses during recognition testing for original sentences (correctly recognized) and inferences (incorrectly recognized). Observers responded "yes" when they thought test sentence had appeared verbatim in a story presented earlier. Original sentences were reproduced from story; inferential sentences did not appear in story but were true by implication for experimental group but not for control group. (Data from Ref. 2)

Experimental Results

- Experimental and control subjects did not differ in mean number of "yes" responses to sentences reproduced verbatim from the stories or to unrelated sentences.
- Experimental subjects gave significantly ($p<0.001$) more incorrect "yes" responses (mean of 7.45) to sentences representing inferences from the stories than did control subjects (mean of 2.6).

Variability

No information on variability was given. Significance of the independent variables and interactions was determined by analysis of variance.

Repeatability/Comparison with Other Studies

Similar results have been obtained with a variety of texts and types of inferences.

Constraints

- Ability to discriminate inferences from explicit statements in text decreases as delay between text and testing increases.
- Some verbatim memory is observed for textual material; the amount varies systematically with the reader's purpose, conditions of study, and conditions of text.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Bartlett, F. C. (1932). *Remembering*: a study in experimental and social psychology. London: Cambridge University Press.

*2. Johnson, M. K., Bransford, J. D., & Solomon, S. K. (1973). Memory for tacit implications of sentences. *Journal of Experimental Psychology*, *98*, 203-205.

Cross References

8.123 Reading speed and text memory: effect of information ordering;

8.128 Schema theory of memory for text

8.126 Aids to Text Comprehension and Recall: Review Questions

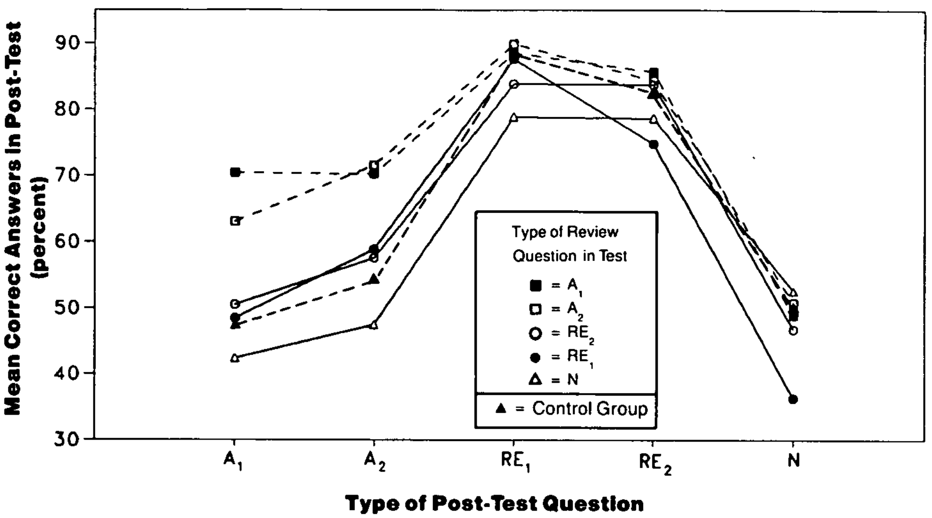

Figure 1. Comprehension and memory for text passages as a function of type of inserted review question. Observers read five text passages and answered a review question after each passage, then took a comprehension memory test covering all five passages. Different curves show type of review questions answered during study of passages; horizontal axis shows type of questions during post-test. Repeat example (*RE*) questions required verification of conceptual information provided in example reproduced from the study passage; application questions (*A*) required generalization of passage information to new example; name (*N*) questions asked only for the name of the psychologist to whom conceptual information was attributed in the passage. Control group (C) did not answer inserted review questions, but did answer same post-test questions as others. (There were two *RE* questions and two *A* questions for each passage.) (From *Handbook of perception and human performance*, adapted from Ref. 2)

Key Terms

Memory aid; reading; text comprehension; text engineering; text recall

General Description

Review questions frequently interspersed with textual material facilitate retention. The type of review question affects the type of learning that is facilitated. Review questions that require the application of material to new situations, rather than memorization and recall, are the most effective.

Applications

Design of instructional materials and programs: diagnosis and training of poor readers.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Five 450-word passages, each describing a different psychological principle
- Multiple-choice questions presented after each passage
- Repeated example (*RE*) questions: the correct alternative exactly reproduced a situation described in text to illustrate a psychological principle; application (*A*) questions: identical to repeated-example questions except a novel situation chosen to illustrate principle; name (*N*) questions: correct alternative was name of the psychologist identified in text
- Observers read a passage in booklet and, without returning to passage, answered a review question; repeated procedure for four other passages; one type of question per observer
- Post-test consisted of five questions about each passage (2 *RE*'s, 2 *A*'s, 1 *N*) identical to review questions; all observers answered same questions
- Control observers did not see or respond to review questions

Experimental Procedure

- Latin square design
- Independent variables: type of review questions, type of post-test questions
- Dependent variable: percentage of post-test questions answered correctly
- Observer's task: read passages, answer review questions, and answer post-test questions
- Observers: 300 high school seniors; no education in psychology; none below average achievement level

Experimental Results

- Overall, observers who answered application review questions during the reading of a passage show the best performance during post-test ($p<0.05$), regardless of the type of post-test question. The advantage of application review questions is particularly evident when the post-test questions are also application questions ($p<0.01$) (Fig. 1).
- Observers who answered name review questions during study of the passages showed the poorest retention, scoring even lower on the post-test than a control group who only read the study passages and answered no review questions.

Variability

Significance of difference between question types was determined by analysis of variance.

Constraints

- Applications questions were more difficult than the other types of questions (they were answered correctly less often during the study of the passages); thus, observers who studied passages with this type of review question may have had greater motivation to attend to the study passages because they had to answer more difficult questions during study.

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Cross References

8.120 Reading speed and accuracy: effect of performing a concurrent task;

8.123 Reading speed and text memory: effect of information ordering;

8.124 Sentence comprehension: effect of syntactic structure;

8.127 Aids to text comprehension and recall: summaries and advance organizers;

Handbook of perception and human performance, Ch. 29, Sect 7.1

8.127 Aids to Text Comprehension and Recall: Summaries and Advance Organizers

Table 1. Effectiveness of supplementary aids for text comprehension and recall.

Instrument	Effectiveness	Source
Abstracts, summaries	Little research done on effectiveness as supplements, but probably are beneficial As substitutes for text, lead to superior retention of explicitly stated information, but inferior retention of implicit information compared to reading text itself (as measured by success in answering true/false questions) Summaries are more effective as background for further summaries than for full text and vice versa	Refs. 7, 9
Advance organizers	Results are quite mixed and contradictory; may be effective when reader does not know what prior knowledge is relevant to the text	Refs. 3, 8
Titles	Effective in improving comprehension of passages specifically designed to be difficult to relate to existing knowledge: title makes topic clear	Refs. 5, 6
Flow charts	Effective as previews for some kinds of materials, but not as substitutes for prose	Refs. 4, 10
Adjunct questions	Effective in facilitating retention of information needed to answer questions; particularly useful where reader motivation is low because adjunct questions explicitly direct attention. Comprehension and retention of material *not* needed to answer questions may be inhibited, facilitated, or unaffected	Ref. 1

Key Terms

Memory aid; reading; text comprehension; text recall

General Description

A variety of supplementary aids have been designed to improve reading comprehension when provided in advance of text. These include:

Abstract or summary: a short passage that conveys the main ideas that will be encountered

Advance organizer: a brief passage that relates new material in the text to knowledge the reader already possesses

Flow chart: block diagrams of the relations among central concepts

Title: a direct description of the major topic

Adjunct question: question given in advance and designed to direct the reader's attention to particular events described in the text.

The table summarizes the effectiveness of these instruments in improving text comprehension and recall. In general, when properly chosen, these aids facilitate text comprehension.

Applications

Design of documentation and textual material to improve readability and comprehension; training of poor readers.

Constraints

- Effectiveness of each aid depends upon the compatibility and quality of the aid with regard to the particular text (Ref. 2).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

8.126 Aids to text comprehension and recall: review questions;

8.128 Schema theory of memory for text

8.128 Schema Theory of Memory for Text

Key Words

Reading; text comprehension; text engineering; text recall

General Description

According to a generalized schema theory of memory for text, what is encoded or stored in memory when text is read is strongly determined by a guiding schema or knowledge framework (that is, the general knowledge a person possesses about a particular domain). When text is read, only a highly selected subset of the information is actually stored in memory, and a single unified representation of meaning, not a verbatim record, is available for recall. According to schema theory, there are four central encoding processes in memory: selection, abstraction, interpretation, and integration.

Selection

When one reads a text, it is processed sequentially: on each fixation, one or two words are encoded in short-term memory. Initially, the words are stored verbatim in the form of phonological or articulatory codes for individual words. Then, during selection, activated schemata—domain-related prior knowledge and expectations—guide decisions of which information should be encoded. For example, important schema-relevant concepts are more likely to be stored than trivial concepts. Much of the original message is simply not represented in memory.

The selection of textual information for encoding is influenced by several factors:

- The existence of relevant schema. Providing subjects with background information or strategies to link new information with already stored information greatly enhances memory
- Activation of a relevant schema by appropriate contextual clues (semantic or structural)
- Importance of incoming information related to the schema
- Consistency of incoming information with one's expectations about that domain
- Amount of attention one gives to an item
- Ability to relate sentences to one another

Abstraction

Information selected because of its relevance and importance is further reduced during encoding by abstraction. Using syntactic and semantic cues, the message is divided into constituents (phrases, clauses, sentences). Clauses and sentences appear to be important "chunks" of information, as eye fixation time is longest at the boundaries between these constituents (Ref. 1). Useful signals to constituent boundaries, such as complementizers (*that*, *which*) aid in comprehension. In addition, separating constituents by extra spaces improves comprehension by poor readers (Ref. 5). The constituents or "chunks" of information enter long-term memory, where the reader's schemata condense the full meaning into its gist, and the actual sentence structure is lost. The constituents (propositions and their relations) are arranged (linked) hierarchically based on importance of the concept, its frequency, relevancy, and recency. Thus, the original message is stored as an abstract representation of the inferred meaning, not as the exact words presented. Experimental studies support this view. Very soon after reading a short paragraph, readers are generally unable to discriminate originally presented sentences from paraphrases of the sentences though memory for the content is excellent (Ref. 4); this effect also depends upon the reader's purpose (reading only for comprehension or reading to commit the text to verbatim memory). In addition, abstraction is indicated by the dramatic decline in verbatim memory for a phrase during a memory probe task if it is not part of the clause currently being processed (Ref. 8).

Interpretation

Encoded information is interpreted based on activated schematic knowledge. Such interpretation may lead to pragmatic inferences, in which explicitly stated information is elaborated and converted into its underlying intent. Conversely, inferences may be made during comprehension to make vague information concrete, to fill in missing detail, or to simplify complex information. Such inferences can lead to constructive errors, as information is added to the memory of a complex event (text) even though it was not presented with the original description of the event.

Integration

Finally, the remaining semantic content is combined with previously acquired, related information that was activated during encoding. Individual ideas ultimately cease to exist and are incorporated into a complex semantic whole. Once integration is complete and old knowledge has been altered or updated, accurate retrieval of the specific information actually presented is highly unlikely. On a memory test, sentences consistent with the integrated representation of a text are judged to have been part of a passage originally presented.

Thus, three sources of information contribute to a single integrated representation of the overall intent of the message: selected propositions of the message, the reader's interpretations of these propositions, and the reader's general knowledge about the event or topic contained in the message. As a result, the reconstructed message or paraphrase is not always free from distortion (Ref. 3). In general, the factors influencing what tends to be remembered in a text include:

Nature of connections established during encoding
Importance of an idea
Sequence in which information is presented
Number and distribution of rehearsals
Task demands, such as instructions
Reader's goals, such as comprehension or memorization

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Design of documentation and textual materials to improve readability and comprehension.

Constraints

• Memory appears to contain more syntactic and lexical detail than the abstract nature of the schema theory predicts.
• No single theory of memory sufficiently accounts for accuracy and distortion.
• At least some details are stored regardless of the extent of one's prior knowledge and regardless of whether that knowledge is activated at encoding.
• Memory appears to contain far more syntactic and lexical detail than is consistent with the view that memory is highly abstractive, in contrast to a central assumption of schema theory (Ref. 2).
• Only recently have researchers begun to experimentally investigate how schemata are acquired or used during text comprehension and retrieval.
• Original support for schema theory encoding processes stems from procedural peculiarities of landmark studies, whose results have not always been replicated by other investigators.

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Cross References

8.117 Factors affecting reading time for sentences;

8.123 Reading speed and text memory: effect of information ordering;

8.124 Sentence comprehension: effect of syntactic structure;

8.125 Memory for inferences made during text reading

8.129 Measurement of Text Readability

Table 1. Formulas for computing text readability.

Name	Description	Source
Flesch formula for reading ease	Reading ease (RE) = 206.835 − 0.846wl − 1.015sl, where wl = number of syllables per hundred words sl = average number of words per sentence	Ref. 4
Dale-Chall formula	X_{c50} = 0.1579x_1 + 0.495x_2 + 3.6365, where X_{c50} = reading grade score of a pupil who could answer half the test questions on a passage correctly x_1 = Dale score (percentage of words outside the Dale list of 3000) x_2 = average sentence length in words	Ref. 3
Devereaux formula, specifically designed for easy computerizing of the algorithm	Grade placement = 1.56wl + 0.19sl − 6.49, where wl = word length in character spaces sl = sentence length in words	Ref. 9
FORECAST readability formula, designed for U.S. Army materials	Reading grade level (RGL) = 20.43 − (0.11) x_1, where x_1 = number of one-syllable words in a 150-word passage	
Gunning's Fog Index	Reading grade level (RGL) = 0.4 (average sentence length + percentage of words having three or more syllables)	Ref. 6

Key Terms

Dale-Chall readability index; Devereaux readability index; Flesch readability index; FORECAST readability index; Gunning's fog index; readability; reading; text engineering

General Description

Readability formulas quantify the difficulty of text based on the frequency of language elements. Word difficulty and/or sentence complexity are typically measured. The most valid formulas measure both word difficulty and sentence complexity, but not much predictive validity is gained by increasing the number of variables beyond those two (Ref. 6). The predictive validity of readability formulas has traditionally been measured in one of two ways. The formula may be applied to reading material for which readability has already been determined by extensive testing. The standard lessons of McCall and Crabbs (Ref. 7) are most commonly used. Alternatively, a cloze procedure may be used in which every fifth word of text is deleted and the readability of the material is ranked by readers' success in guessing the deleted words. The success rate is then correlated with the formula's predictions. The measures presented in Table 1 generally yield correlations of 0.6-0.8 when measured against McCall-Crabbs standards and somewhat higher values with cloze procedures (Ref. 6).

Formulas express readability in a variety of ways, usually as a reading grade-level equivalent. That is, a text should be readily understandable by the average person who has attained the indicated grade level (Ref. 3).

Word difficulty is often measured by word length and familiarity (percentage of a text's words which are on a standardized list of familiar words). Sentence complexity usually is reflected in sentence length. Generally, a text is evaluated by applying a formula to a 100-200 word sample. Table 1 lists some representative readability formulas. Table 2 shows results of each formula for a given passage (Ref. 5).

Applications

Evaluation of documentation and textual materials.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Merely reducing sentence length does not appear to increase readability as measured by comprehension tests; shorter words tend to be more familiar, but there is no other effect of word length (Ref. 8).
- It is not valid to edit or write text using a formula to achieve a certain grade level of readability; however the narrow view of readability promoted by formulas has led to such abuses (Refs. 5, 8).
- Consideration of audience characteristics (background knowledge, etc.), use of headings, explicit statement of a purpose, use of topic in subject position of sentence, consistent use of terminology, linking of the unfamiliar to the familiar by analogy, and a variety of other techniques which improve comprehension are not measured by readability formulas (Ref. 5).

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Table 2. Readability scores for sample passage as computed from five different formulas. (From Ref. 2)

100-Word Sample Passage

As staggering as casualty figures for Civil War battles are, even more appalling are the statistics of deaths from disease. It has been estimated that two and one-half Union deaths resulted from disease for every single combat loss, while the ratio on the Confederate side was three to one. The North Carolina soldier who wrote that "these big battles is not as bad as the fever" knew of what he told.

Clara Barton, who would later found the American Red Cross, left her Patent Office desk to find means of channeling medicine to the sick and wounded; and Sally....

Formula	Score	Comments
Flesch	49.5	Scores can range from 100 (easy) to 0 (difficulty); this is a passage of average difficulty
Dale-Chall	7.23	Equivalent to reading grade of a reader who could answer half of a set of comprehension questions
Devereaux	8.38	Reading grade level
FORECAST	9.43	Reading grade level
Fog Index	16.0	This reading grade-level differs considerably from other estimates and reflects a heavy weighting for sentence length.

8.201 Acoustic Properties of Speech

Key Terms

Acoustic speech properties; coarticulation; formant; speech perception; speech signals

General Description

The speech signal is a continuous acoustic waveform. It has both a fundamental frequency, or pitch (F_0), and concentrations of energy known as **formants** centered at frequencies that are multiples of F_0 determined by the resonance characteristics of the vocal tract. The speech signal contains slowly changing, intense, quasi-periodic patterns associated with vowels and rapidly changing, less intense, aperiodic elements such as bursts, silence, and noise (or turbulence) associated with consonants. The intensity (amplitude) of the signal can vary as a whole, or the intensity of a portion of the frequency range can vary relative to the rest of the spectrum. Table 1 describes the primary characteristics of the three physical dimensions of the acoustic signal (the speech waveform).

The task of the listener is to segment the speech waveform into meaningful units of the language. Gaps in the acoustic signal do not regularly correspond to word or syllable divisions; the sounds are not discrete events, but merge into each other. Both factors increase the difficulty of the listener's task.

Coarticulation (shown diagrammatically for the word *bag* in Fig. 1) means that the acoustic energy of different **phonemes** (smallest meaningful units of sound) overlaps in time and that the acoustic signal for a given phoneme is altered in different contexts; this makes it difficult to find invariant acoustic features for phonetic segments. At normal rates of speech, the articulators, such as the tongue and lips, change position 10-20 times per second; this rapid movement means that one sound has to be begun before another ceases and that an articulator does not return to a neutral position between sounds. Although this adds complications to the perception of speech, coarticulation codes the order of phonetic segments.

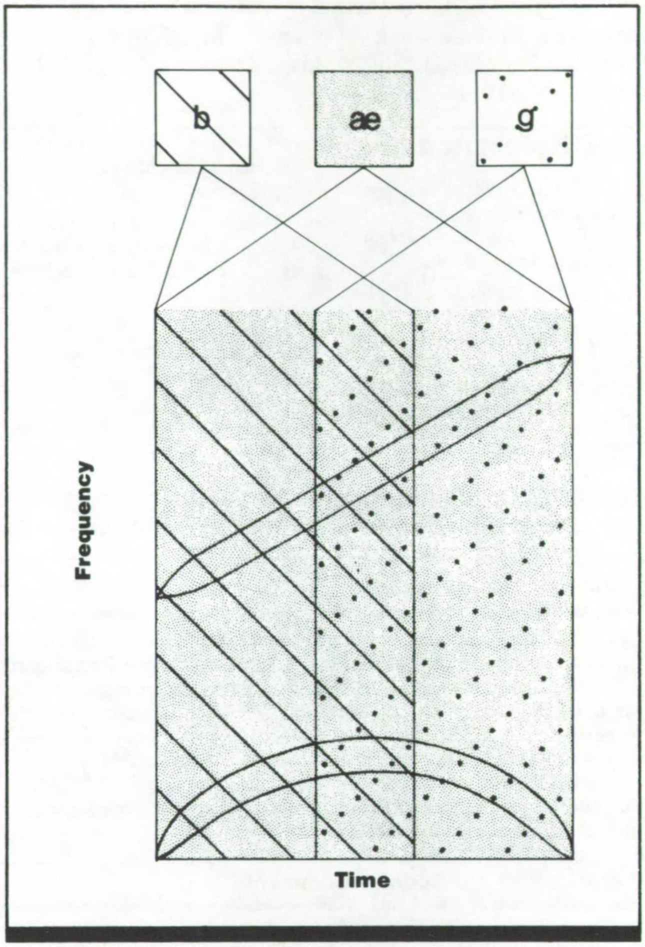

Figure 1. Schematic portrayal of the word *bag* showing the portions of the acoustic signal corresponding to each phoneme. The overlap of the phonemic segments (coarticulation) means that acoustic cues for more than one phoneme are present at the same time. (From Ref. 5)

Constraints

- There is considerable individual variation in all three dimensions of the speech signal.
- The intensity necessary for speech to be intelligible depends on many variables (e.g., background noise, the predictability of the message, speaker's enunciation; CRef. 8.304).
- The filtering characteristics of the transmission system must be considered. For example, not all frequencies in the speech waveform are passed by telephone lines.

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Cross References

8.202 Methods of analyzing the speech signal;

8.206 Phones and phonemes;

8.304 Factors affecting the intelli-. gibility of speech in noise;

Handbook of perception and human performance, Ch. 27, Sect. 1.1

Table 1. Primary dimensions of the acoustic signal.

	Physical Dimension			
	Duration	**Intensity**	**Frequency**	
Perceptual Correlate	Length	Loudness	Pitch	Quality*
Most common measure	Milliseconds (msec)	Decibels (dB) sound pressure level (SPL); O db = 10^{-16} W/cm^2	Hertz (Hz)	
Normal range	10-20 phonemes per second	30-80 dB SPL	250 Hz - 9 kHz (mostly below 4 kHz)	
Relative differences	Vowels 30-300 msec; consonants 10-100 msec	23-27 dB SPL difference between vowels and consonants; vowels 50-80 dB; consonants 30-60 dB	Fundamental frequency (F_0) averages 100 Hz for males, 200 Hz for females, can extend as high as 400 Hz	Formants (concentrations of energy) at 500, 1,500, 2,500, etc., for males; 600, 1,800, 3,000, etc., for females

*Quality is determined by the resonance characteristics (formant patterns) of different configurations of the vocal tract.

8.202 Methods of Analyzing the Speech Signal

Key Terms

Acoustic invariants; dynamic spectra; sound spectrogram; spectral features; speech perception; speech signals

General Description

In speech perception, the listener transforms a continuously changing acoustic waveform into a message (CRef. 8.201). Coarticulation of **phonemes**, other context effects, and within-and between-speaker variables alter the acoustic features, yet do not significantly interfere with phonetic perception. Several methods have been used to analyze the speech signal in an effort to find acoustic invariants for phonetic features (i.e., acoustic patterns that correlate with given phonetic segments).

The sound spectrogram (Fig. 1) is a visual representation of the speech waveform. Time is shown along the abscissa and frequency along the ordinate. The intensity of acoustic energy at a given time and frequency is proportional to the darkness of the trace. The narrow vertical lines represent vocal cord vibration.

The sound spectrograph has a microphone that picks up speech sounds and a set of filters covering the frequency range from high to low. Each filter passes energy in a narrow frequency band; the output voltage of each filter determines the brightness of a small light, which leaves a trace on a moving belt of phosphorus. The set of lights covers the width of the phosphorus band and the pattern formed in the phosphorus constitutes the spectrogram. Analysis of the speech signal by means of the spectrogram involves the identification of patterns of acoustic energy characteristic of the different vowels and consonants. These patterns are comprised of information such as the presence or absence of periodic or aperiodic noise, the existence of silent periods, rapid changes in spectral frequency, etc. Patterns that correspond to manner of articulation (the rows in Fig. 2), place of articulation (the columns in Fig. 2), and voicing for consonants (although these are not stable across different vowel contexts), can be isolated. Relatively stable formant patterns (concentrations of energy) can be defined for vowels. The degree to which phonetic features can be specified in terms of characteristics of the spectrogram is rather general; the spectrogram tends to be more useful for vowels than for consonants.

The spectrum envelope is another visual representation of speech. The spectrum envelope can be described as a static two-dimensional representation (Fig. 3) of frequency and amplitude averaged over some period of time or as a dynamic three-dimensional plot (Fig. 4) of frequency, time, and amplitude. Unlike the spectrogram, which allows individual components in the signal to be isolated, acoustic properties tend to be integrated in the spectrum envelope, which may more nearly represent the information as it is used by the auditory system.

Analysis of the spectrum envelope has concentrated on the configuration of the envelope of consonants, to identify their invariant acoustic properties. The static approach assumes that the listener samples speech at the points where there is most rapid change in amplitude or in the spectrum because relatively more information is available there; the acoustic invariants sought are those that correlate with articulatory features (e.g., place of articulation) or distinctive features (e.g., front/back). In Fig. 3, the spectral shapes at the onset of stop consonants were sampled using a time window with a width of 26 msec. Varied vowel contexts were used in syllables consisting of a consonant followed by a vowel (e.g., *di*); samples from several speakers were used. Templates were devised for place of articulation by isolating the features for the **labial** stops (/b/ and /p/) that did not change over samples from those that did. Templates were also derived for **alveolar** and **velar** stops. New samples of the syllables were matched with the templates. The success rate for syllable initial stops was 83%; when the same stop consonants followed the vowel in vowel-consonant syllables, however, success of template matching dropped to 53-76%.

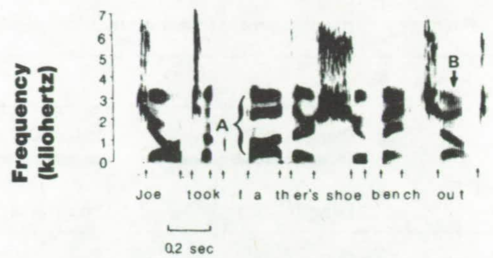

Figure 1. A sound spectrogram for the sentence, "Joe took father's shoe bench out." Frequency is shown as a function of time. Increasing intensity is represented by increasing darkness of the trace. The horizontal bars such as those at *A* are concentrations of energy representing formants; the small vertical bars such as those at *B* represent periodic laryngeal pulsing. The vertical arrows along the abscissa indicate locations of rapid frequency changes, which may indicate the presence of consonants. (From Ref. 6)

Dynamic approaches to acoustic analysis place a great deal of emphasis on the way the acoustic signal is filtered by the peripheral auditory system. One model (Ref. 4) used a series of 1/3-octave filters that were updated at 1.6-msec intervals, but this gave too much detail, so the data were averaged over every five frames (i.e., equivalent to an 8-msec period). From these data, running spectra for a number of consonant-vowel syllables were computed (Fig. 4). (Another dynamic system [Ref. 3] used 1/4-octave bandwidth filters and a time frame of 5 msec). Success rates in matching novel samples to features specified in the running spectra range from 100% for the dimension of voicing to 78% for place of articulation of the stop consonants in syllable-initial position.

Dynamic models, like static ones, analyze the spectrum envelope for acoustic features that correlate with articulatory or distinctive features. They limit the contexts across which invariance is to be expected. Features that contribute to the perception of certain stop consonants in syllable-initial position may not be the same for the stop consonants between vowels or in syllable-final position.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

8.201 Acoustic properties of speech;

Handbook of perception and human performance, Ch. 27, Sects. 1.1, 5.1, 5.3

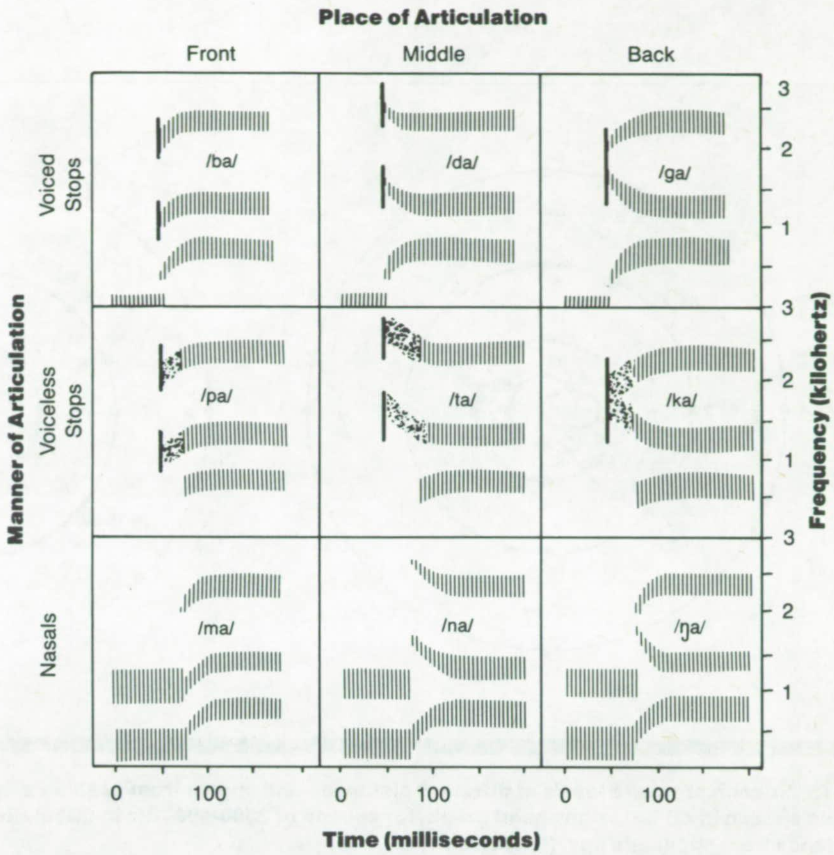

Figure 2. Spectrograms for syllables containing the same vowel but different consonants. Each syllable is identified by manner of articulation (rows) and place of articulation (columns). (From Ref. 3)

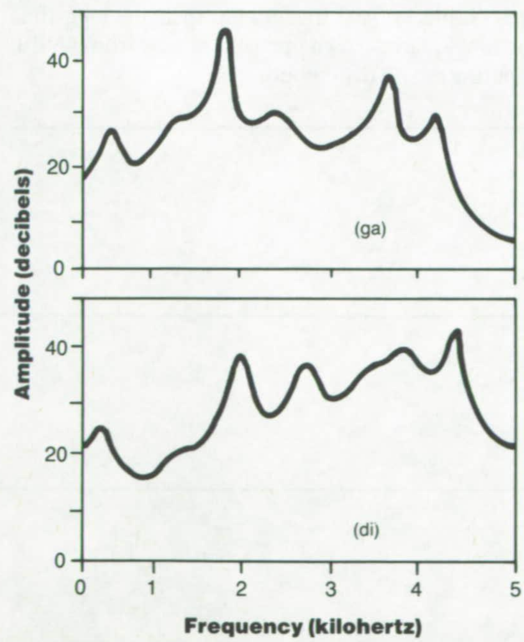

Figure 3. Static spectrum envelopes for the syllables *ga* and *di*. Amplitude (averaged over a given time interval) is shown as a function of frequency. (From Ref. 1)

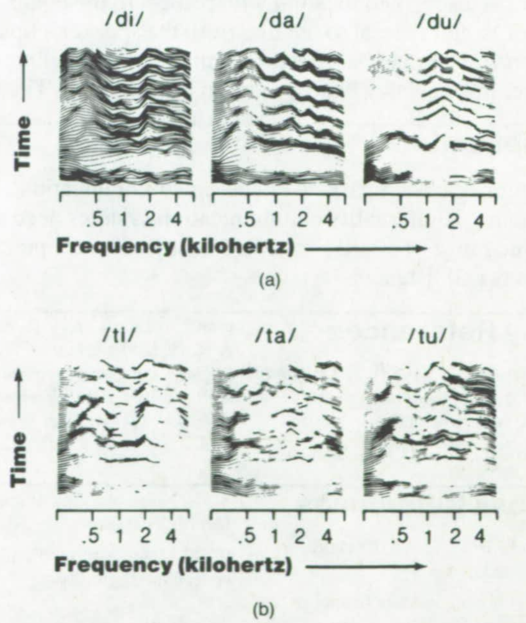

Figure 4. Dynamic spectra for two sets of syllables. Amplitude (height) is shown as a function of frequency and time. (From Ref. 5)

8.203 Sound Pressure of Normal Adult Speech

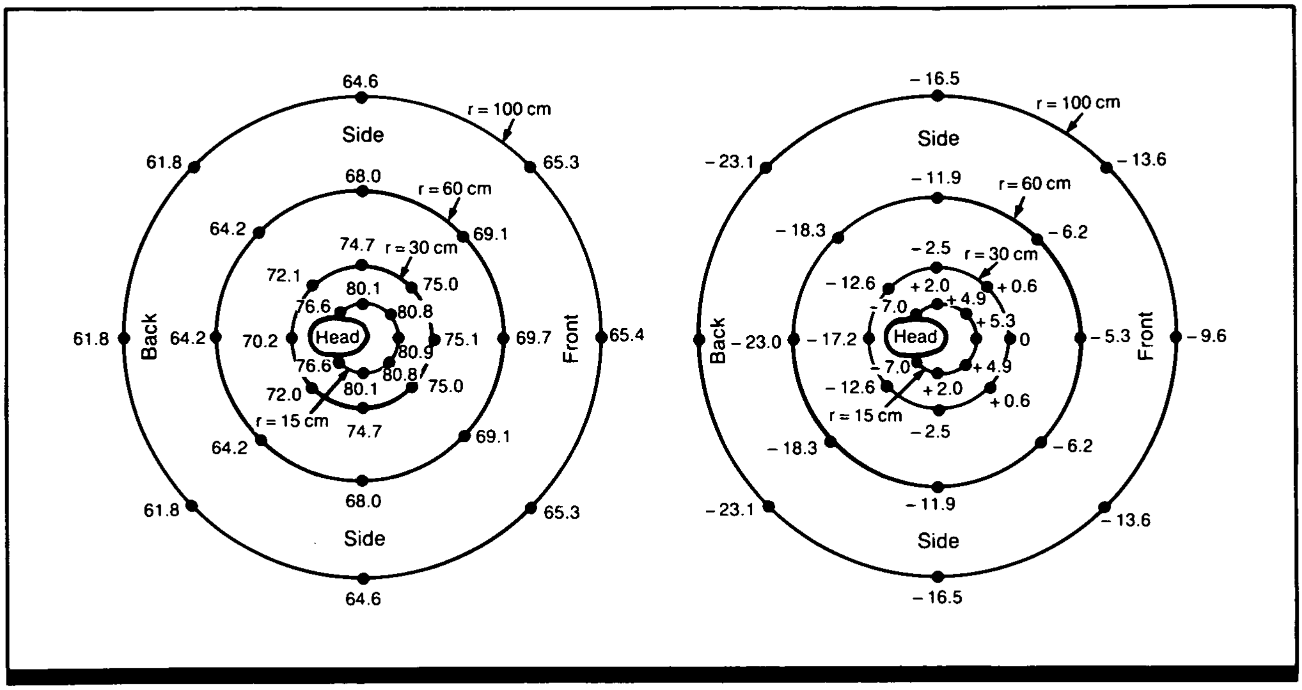

Figure 1. Speech pressure levels at different distances and angles from speaker's lips. Left-hand diagram shows results for whole speech in dB SPL; right-hand graph, for speech of 2800-4000-Hz in dB relative to level at 30 cm in front of lips. *r* = distance from speaker's lips. (From Ref. 1)

Key Terms

Speech level; speech production

General Description

Speech pressure is defined as the force exerted by the sound wave at a specified location with respect to the talker, usually 1 m and normal to the line from the speaker's lips. Speech level may be measured with a sound level meter, either in frequency bands, or as an overall level. The weakest speech sound is /θ/ as in *thin*. The levels of other phonemes (expressed relative to the level for /θ/) range from 20-28.2 dB for vowels and semivowels to 0-19 dB for consonants (Table 1). At 1 m from the speaker, long-time root-mean-square speech pressure ranges from 46 dB (whispering) to 86 dB (shouting).

Applications

Designing or comparison of speech communication systems. High-quality communication systems need a dynamic range of 60 dB, but 20 dB is sufficient for practiced talkers and listeners.

Key References

1. Fletcher, H. (1953). *Speech and hearing in communication*. New York: Van Nostrand.

2. Kryter, K. D. (1972). Speech communication. In H. P. Van Cott & R. G. Kinkade (Eds.), *Human engineering guide to equipment design* (pp. 161-226). Washington, DC: U.S. Government Printing Office.

Cross References

2.103 Measurement of sound amplitude;

8.204 Sound pressure of speech for males and females;

8.310 Noise masking of speech: effect of vocal force;

8.317 Methods of predicting speech intelligibility

Table 1. RMS pressure levels for some English phonemes. (From Ref. 2)

Key Word	Sound*	Pressure level (dB)	Key Word	Sound*	Pressure level (dB)
talk	o′	28.2	chat	ch	16.2
top	a	27.8	me	m	15.5
ton	o	27.0	jot	i	13.6
tap	a′	26.9	azure	zh	13.0
tone	o	26.7	zip	z	12.0
took	u	26.6	sit	s	12.0
tape	a	25.7	tap	t	11.7
ten	e	25.4	get	g	11.7
tool	u	25.0	kit	k	11.1
tip	i	24.1	vat	v	10.8
team	e	23.4	that	th	10.4
err	r	23.2	bat	b	8.0
let	l	20.0	dot	d	8.0
shot	sh	19.0	pat	p	7.7
ring	ng	18.6	for	f	7.0
			thin	th	0

*Spoken by an average talker at a normal level of effort.

Table 2. Sound pressure levels of speech 1 m from the speaker. (From Ref. 2)

Measure of Sound Pressure	Whisper (dB)	Normal Level (dB)			Shout (dB)
		Minimum	Average	Maximum	
Peak instantaneous pressure	70	79	89	99	110
Speech peaks	58	67	79	87	98
Long-time root mean square pressures	46	55	65	75	86
Speech mimina	30	39	49	59	70

Table 3. Distribution of speech levels for persons using the telephone. (From Ref. 2, based on Ref. 1)

Percent of Talkers	Level Range (dB SPL)*
7	Below 54
9	54-57
14	57-60
18	60-63
22	63-66
17	66-69
9	69-72
4	72-75
0	Above 75

*Measured at a point 1 m from the talker's lips.

8.204 Sound Pressure of Speech for Males and Females

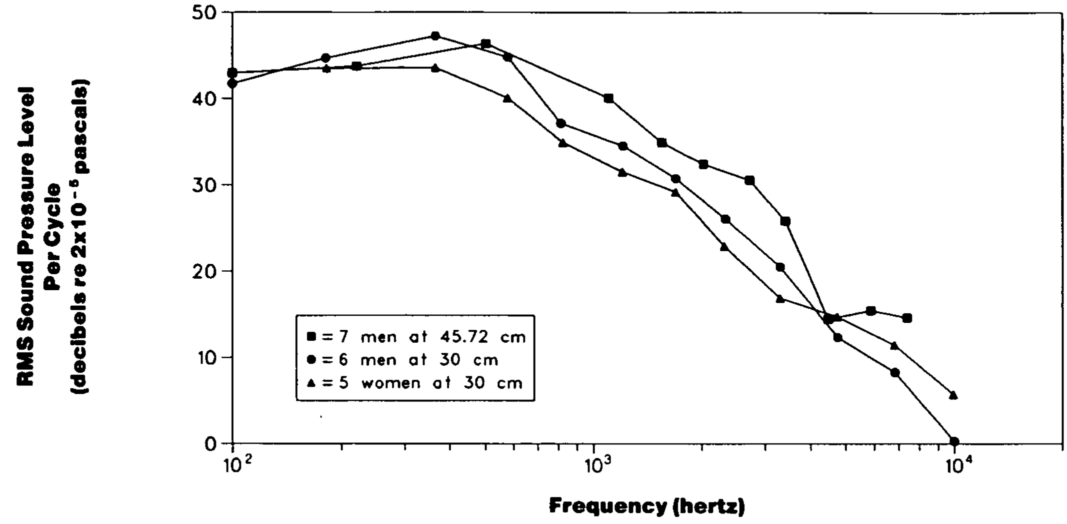

Figure 1. The intensity levels of normal adult speech as a function of frequency. (From Ref. 4)

Key Terms

Sound frequency; speech level; speech production

General Description

Intensity of human speech is greatest for frequencies in the 100-1,000-Hz range and decreases steadily as frequency increases above 1,000 Hz. The relationship holds for males and females, although measured intensities are, on the average, about 3 dB sound pressure level (SPL) less for female speakers.

Applications

Design or comparison of speech communication systems.

Methods

Test Conditions

- Condenser microphone, placed 45.72 or 30 cm from speaker, in a relatively sound-attenuating room
- Output voltage separated into one-octave bands <500 Hz and one-half octave bands >500 Hz
- 600 peak observations made in each band

Experimental Procedure

- Independent variables: distance from microphone, gender of speaker
- Dependent variable: root mean square sound pressure level per cycle in dB re 20 μPa for each band
- Subject's task: read prose in a normal speaking voice
- 13 male and 5 female subjects

Experimental Results

- Speech energy is concentrated in 300-600 Hz frequency range.
- As frequency increases >600 Hz, speech energy steadily decreases.
- Measured speech energies are ~5 dB SPL less for females than for males, in the 100-1,000-Hz range. Above 1,000 Hz, the difference between males and females is ~2 dB.

Variability

No specific information provided, but between-subject variability is high, as much as 18 dB for some frequency bands (Ref. 1).

Repeatability/Comparison with Other Studies

Results presented here have been confirmed in several studies under similar conditions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Results apply only to measurements taken over long speech samples; energy distribution in brief speech segments may differ markedly.

Key References

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2. French, N. R., & Steinberg, J. C. (1947). Factors governing the intelligibility of speech sounds. *Journal of the Acoustical Society of America, 19*, 90-119.

3. Kryter, K. D. (1972). Speech communication. In. H. P. Van Cott, & R. G. Kinkade (Eds.), *Human engineering guide to equipment design* (pp. 161-266). Washington, DC: U. S. Government Printing Office.

*4. Licklider, J. C. R., & Miller, G. A. (1951). The perception of speech. In S. S. Stevens, (Ed.), *Handbook of experimental psychology*, (pp. 1040-1074). New York: Wiley.

Cross References

8.203 Sound pressure of normal adult speech;

Handbook of perception and human performance, Ch. 26, Sect. 4.2

C-2

8.205 Articulatory Features of Speech

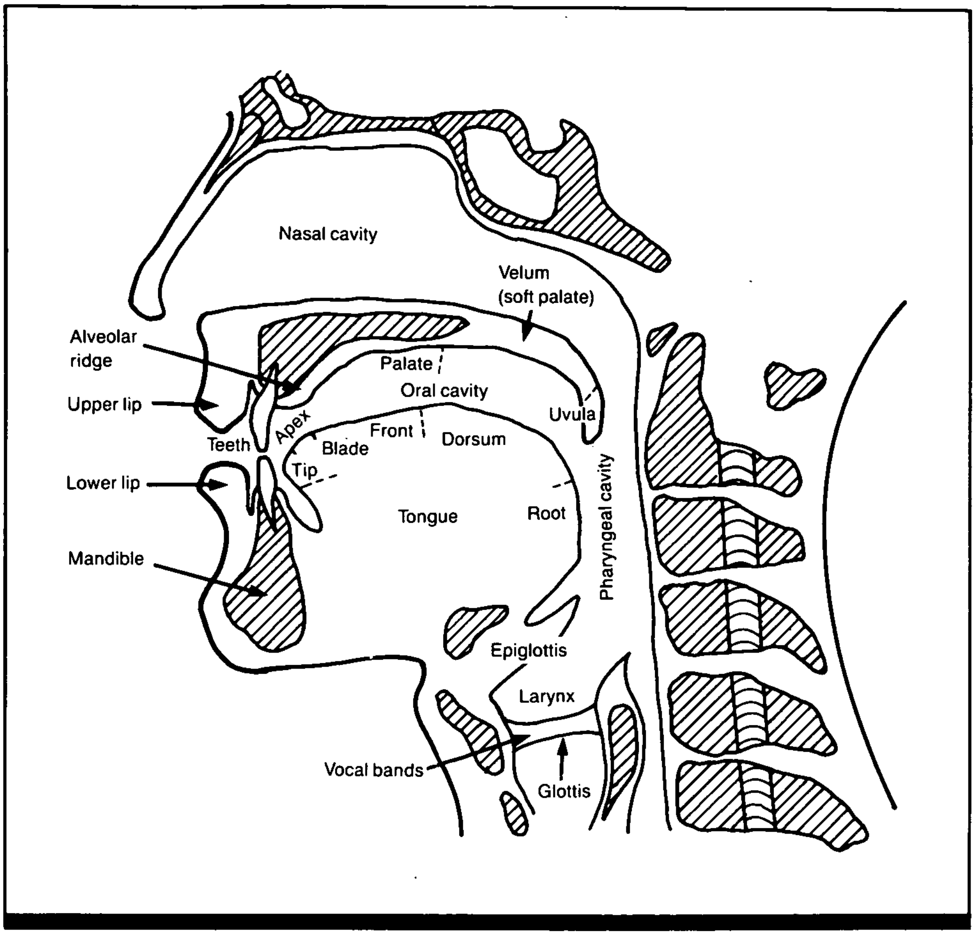

Figure 1. The principle organs controlling the production of speech. (From Ref. 3)

Key Terms

Affricate; articulatory feature; consonant; diphthong; fricative; liquid; nasal; place of articulation; semivowel; speech articulation; speech production; stop; vocal effort; vocal tract; voicing glide; vowel

General Description

The vocal tract behaves in accordance with the physical principles governing the filtering and resonance characteristics of acoustic tubes. Each speech sound has a source that generates an acoustic waveform which is filtered by the vocal tract. This waveform can be periodic (or quasi-periodic) or aperiodic. Periodic waveforms are produced when air is forced from the lungs through the larynx, causing the vocal cords to vibrate (voicing). Aperiodic waveforms, which may arise at a variety of locations in the vocal tract, are caused either by a narrow constriction in the vocal tract that creates turbulence and produces a hissing sound (noise) or by a complete closure of the vocal tract followed by a forceful opening (burst). Because the mechanisms for producing speech function as a parallel system, it is possible for a burst to be voiceless (as in /p/), or voiced (as in /b/).

The portion of the vocal tract above the larynx, the supralaryngeal tract, varies in length from 17.5 cm in the adult male to 14.75 in the adult female, and 8.75 cm in infants. It also varies in cross-sectional size and in shape. Both length and configuration contribute to the acoustic filtering characteristics. Movements of the tongue, lips, or other articulators (the moveable anatomical parts that shape the speech waveform) can completely close the vocal tract or narrow it at one location while widening it at another.

The human speech mechanism (shown is cross section in Fig. 1) can be considered as a pump (the lungs) that passes air through a tube made up of three cavities (the pharyngeal, oral, and nasal cavities) and containing four valves (the laryngeal, lingual, labial, and velar), which are the four major articulators (the larynx, tongue, lips, and velum, respectively). Classification of speech sounds on the basis of the way in which the sounds are produced focuses on three

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

articulatory features: (1) manner of articulation; (2) place of articulation; and (3) presence or absence of voicing.

Manner of Articulation

Table 1 shows the types of waveforms (periodic laryngeal pulsing, noise, or bursts) associated with the categories of speech sound classified by manner of articulation.

Vowels are produced by laryngeal pulsing (vocal cord vibration); the flow of air through the vocal cavity is relatively unimpeded. Two vowels produced without an intervening consonant are called a **diphthong**.

With consonants, the flow of air in the vocal tract is closed off completely, severely restricted, or both. Glides (/w/, /j/, /r/, /l/) are produced in a manner very similar to that of vowels because their only sound source is laryngeal pulsing; thus they are sometimes called semivowels. They are similar to consonants in that they are usually shorter and less intense than vowels. Glides are sometimes divided into glides (/w/,/j/) and liquids (/r/,/l/).

Nasals (/m/,/n/,/ŋ/) also have only laryngeal pulsing as a sound source, although they involve complete closure of the vocal tract at some point; but they are produced by lowering the velum, which opens an acoustic side branch (the nasal cavity) that changes the resonance characteristics of the vocal tract. Although English has no nasal vowels, they do occur in other languages (e.g., French).

Fricatives are produced by a narrow constriction at some place in the vocal tract, which creates turbulence; they may or may not be accompanied by simultaneous laryngeal pulsing. Stops are produced by a complete closure at some place in the vocal tract, which creates silence followed by a burst. The affricates are essentially sequences of stop-fricative, and therefore are sometimes classified as blends rather than as unique **phonemes.**

Place of Articulation

All speech sounds are produced at locations of the vocal tract where great variability of articulation produces only small changes in acoustic output; this allows for considerable imprecision in articulation (Ref. 5).

Consonants are classified according to the location at which the flow of air is restricted or stopped:
- bilabial—lip on/near other lip
- labiodental—teeth on/near lip
- dental—tongue on/near teeth
- alveolar—tongue on/near aveolar ridge
- palatal—tongue on/near hard palate
- velar—tongue on/near soft palate (velum)
- glottal—bursts or turbulence at larynx

(There are other locations as well that do not apply for English phonemes.)

Vowels are classified according to height of tongue (high to low) and location where tongue is highest (front to back).

Presence or Absence of Voicing

Consonant pairs that share the same manner and place of articulation are differentiated from each other by being voiced or voiceless (e.g., the bilabial stops /p/ and /b/ differ only in that /b/ is voiced).

All vowels are voiced. Vowels can also be classified as short or long in duration, lax or tense, and rounded or unrounded. Lax vowels are produced with the tongue near a neutral position, and all lax vowels are short. Tense vowels are produced with the tongue extremely far from a neutral position, and they are all long. Four of the five back vowels in English are produced with the lips rounded; all other vowels are typically unrounded.

Constraints

- Classification by articulatory features makes sense in terms of production, but may not be the most useful approach to understanding speech perception.
- Different articulatory maneuvers may be used to produce the same acoustic consequence.

Key References

*1. Dale, P. S. (1976). *Language development*. New York: Holt, Rinehart and Winston.

2. Dew, D., & Jensen, P. J. (1977). *Phonetic processing: The dynamics of speech*. Columbus, OH: Charles E. Merrill.

3. Francis, W. N. (1958). *Structure of American English*. New York: Wiley.

4. Ladefoged, P. (1962). *Elements of acoustic phonetics*. Chicago: University of Chicago Press.

5. Stevens, K. N., & Klatt, D. H. (1974). Current models of sound sources for speech. In B. Wyke (Ed.), *Ventilatory and phonatory control systems*. London: Oxford University Press.

Cross References

8.201 Acoustic properties of speech;

8.206 Phones and phonemes

Table 1. Waveforms associated with major categories of speech sounds classified by manner of articulation.

Manner of Articulation	Periodic Laryngeal Pulses (Voicing)	Burst	Noise
Vowels, diphthongs, glides (liquids), and nasals	X		
Unvoiced stops		X	X
fricatives			X
affricates		X	X
Voiced stops	X	X	
fricatives	X		X
affricates	X	X	X

8.206 Phones and Phonemes

Key Terms

Allophone; phone; phoneme; phonetic transcription; phonetics; phonology; speech perception

General Description

The sounds of speech can be graphically symbolized on several levels of abstraction. *Phonetics* attempts the most exact representation of speech segments in terms of a set of discriminable sounds called phones. *Phonology* uses broader categories called phonemes, which are abstract units in that several different phones may be variants of a single phoneme. For example, all phones with differences in pronunciation that do not signal differences in meaning in a particular language are grouped under a single phoneme. The most abstract graphic representation of speech is the alphabet; the letters of the written language have only a rough equivalence to phones or phonemes.

Phones are the smallest discriminable units of sound that can be formed in speech. For example, the phone [p], representing the nonaspirated *p* of *spin*, is different from the phone [p^h], representing the aspirated *p* of *pin*.

- There are hundreds of phones in American English alone; different phones are used for the pronunciations that are idiosyncratic or dialect variants of standard English sounds.
- The graphic symbols representing phones are enclosed in square brackets, as in [p].
- Phonetic transcriptions enable a listener to encode, or a reader to decode, a spoken message in any language, even one whose phonology is unknown to him; all the information necessary to reproduce the pronunciation is included. For example, the phonetic transcription of *coat* is [$k^h o^w t$], which encodes that the initial /k/ is aspirated (produced with a large breath of air) and the vowel /o/ is rounded.

Phonemes are the smallest units of speech that alter the meaning of what is said in a particular language (e.g., the words *bin* and *pin* have different meanings, because one starts with /b/ and one starts with /p/). The phoneme /p/ is a category that includes both the aspirated *p* of *pin*, [p^h], and the nonaspirated *p* of *spin*, [p], because the change in aspiration does not change meaning (i.e., replacing [p] in *spin* with [p^h] or replacing [p^h] in *pin* with [p] changes the meaning of neither word).

- There are approximately 40 phonemes in American English (Table 1); some linguists consider as individual phonemes sounds that others class as blends of two sounds.
- The graphic symbols representing phonemes are enclosed in slashes, as in /p/.
- Phonemic (phonological) transcriptions enable a listener to encode, or a reader to decode, a spoken message in a language only when its phonology is known; the information necessary to reproduce the pronunciation is not encoded. For example, the phonological transcription of *coat*, /kot/, requires the knowledge that, in English, all initial voiceless stops are aspirated and all back vowels except /a/ are rounded.
- When two or more phones are included within one phoneme category of a language, they are called *allophones*. Allophones are perceptibly different sounds, but the differences in pronunciation do not represent differences in meaning. However, the allophones of one language may be different phonemes in another language.
- The sounds of speech are usually perceived on the phonological level.

Constraints

- Systems of notation differ in the graphic symbols used for phonemes.

Key References

*1. Dew, D., & Jensen, P. J. (1977). *Phonetic processing: The dynamics of speech.* Columbus, OH: Charles E. Merrill.

2. Sloat, C., Taylor, S. H., & Hoard, J. E. (1978). *Introduction to phonology.* Englewood Cliffs, NJ: Prentice-Hall.

Cross References

8.205 Articulatory features of speech

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Pronunciation guide to American English phonemes. (From Ref. 1)

Consonants			Vowels		
Common Symbol	**Alternate Symbol**	**As In:**	**Common Symbol**	**Alternate Symbol**	**As In:**
/p/		pet, happy	/i/		even, seen, lead
/b/		book, rabbit	/ɪ/,	/ɩ/	sit, hymn
/t/		ten, letter	/e/		taste, rain, say
/d/		door, hidden	/ɛ/		bed, head
/k/		keep, cow, luck	/æ/		hat, laugh
/g/		good, buggy	/ɝ/		bird, heard
/f/		feet, staff, phone	/ʌ/		cup, some, young
/v/		vowel, of	/u/		boot, rule, move
/θ/		three	/ʊ/,	/ɷ/	book, pull
/ð/		these, clothe	/o/		mote, boat, tow
/s/		six, miss, scene	/ɔ/		ball, jaw, fault
/z/		zoo, as, fuzzy	/a/,	/ɑ/	doll, father
/š/,	/ʃ/	shop, nation, ocean	/ə/*		roses, basket
/ž/,	/ʒ/	fusion, azure, vision			
/h/		house, who			
/č/,	/tʃ/	chalk, nature			
/ǰ/,	/dʒ/	jar, gem, bridge			
/m/		map, hammer			
/n/		new, funny			
/ŋ/		sing, lung			
/w/		wind, quiet			
/ʍ/		whet			
/j/,	/y/	year, onion, use			
/r/		rabbit, hurry			
/l/		long, ball			

*The schwa is often considered the extreme reduction of any vowel and not a unique phoneme.
/ʔ/, the glottal stop, can be heard as the initial sound when words like *and, or, it* are pronounced in isolation, but it is not usually considered a phoneme.

The table contains spelling examples rather than an exhaustive list, and other spellings could be listed.

8.207 Cues and Cue Trading for English Consonants

Key Terms

Affricate; aspiration; consonant; cue trading; fricative; speech perception; stop; vocal effort

General Description

A consonant cue is a specific segment of (or pattern in) the acoustic waveform of an individual **phoneme** that serves to differentiate it from related consonants. Most cues that have been studied are those that can be isolated from sound **spectrograms** of consonants and independently manipulated in a speech synthesizer so that their effect on perception can be controlled. For example, a rapid rise in the first **formant** (F_1) transition distinguishes the **stop** consonant /b/ from the glide /w/, both of which are voiced and articulated in the same place (lips); artificial control of the speed of rise of F_1 allows a boundary area to be defined separating perception of /b/ from perception of /w/. Such consonant cues are usually classed as cues to the articulatory features of production: manner of articulation, place of articulation, and **voicing**.

Different cues signal the same consonant in different contexts. For example, voiceless stops (e.g., /p/) are cued by aspiration when they are in the initial position of a syllable, but aspiration does not accompany the voiceless stops in the final or **intervocalic** position.

Virtually every phonetic contrast is cued by several acoustic properties of the speech signal. When a change in one cue (which would signal a change in phonetic percept) can be offset by a change in another cue so as to maintain the original phonetic percept, a cue-trading relation exists. Tables 1, 2, and 3 list cues that have been found to trade in distinguishing consonants on the basis of voicing/no voicing, place of articulation, and manner of articulation, respectively. Sources where more information can be obtained are identified.

Table 1. Cue-trading relations for the voiced/voiceless distinction.

Manner of Articulation	Context	Cues that Trade	Source
Stop	Initial position in syllable	1. Variation in voice onset time can be offset by changes in: (a) the onset frequency of the F_1 transition; (b) the amplitude of aspiration noise preceding VOT; (c) The F_0 (pitch of fundamental frequency) at the onset of voicing.	Refs. 3, 4, 7
	Intervocalic (between-vowel) position	1. Duration of the preceding vowel 2. Offset characteristics of the preceding vowel 3. Duration of the closure interval (silence marking stop) 4. Amplitude of voicing during closure 5. Onset characteristics of the following vowel	Ref. 5
	Final position	1. Duration of preceding vowel 2. Offset characteristics of preceding vowel 3. Properties of the release burst (if there is one) 4. Duration of the closure preceding release burst	Ref. 6
Fricative	Initial position	1. Fricative noise duration 2. F_0 at onset of periodicity	Ref. 8
	Final	1. Duration of preceding vowel 2. Duration of fricative noise 3. F_0	Ref. 6

Note: Pairs of consonants that share the same manner and place of articulation (e.g., /p/ and /b/) can be discriminated from each other as being voiced (i.e., produced with periodic laryngeal pulsing) or voiceless. Although pairs of stops as well as pairs of **fricative** consonants are discriminated in this way, different cues are utilized because stop consonants have a period of silence from which voice onset time (VOT) can be measured and fricatives do not.

Constraints

- Cues may not function as perceptual entities that are extracted and then recombined (i.e., phonological perception may be more global in nature).
- Many discriminations have not been studied.

Key References

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6. Raphael, L. J. (1972). Preceding vowel duration as a cue to the perception of voicing characteristics of word-final consonants in American English. *Journal of the Acoustical Society of America, 51,* 1296-1303.

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*8. Repp, B. H. (1982). Phonetic trading relations and context effects: New experimental evidence for a speech mode of perception. *Psychological Bulletin, 92,* 81-110.

9. Repp, B. H., Liberman, A. M., Eccardt, T., & Pesetsky, D. (1978). Perceptual integration of acoustic cues for stop, fricative, and affricate manner. *Journal of Experimental Psychology: Human Perception and Performance, 4,* 621-637.

Cross References

8.205 Articulatory features of speech;

8.206 Phones and phonemes

Table 2. Cue-trading relations for place of articulation.

Manner of Articulation	Context	Cues that Trade	Source
Stop	Initial position in syllable	1. Second and third formant transitions 2. Burst frequency 3. Burst amplitude	Ref. 2
	Intervocalic position	1. Formant transitions into the closure 2. Formant transitions out of the closure 3. Closure duration 4. Release burst frequency	Ref. 6
	Between fricative and vowel	1. Offset spectrum of fricative noise 2. Duration of the closure period 3. Formant frequencies at onset of vowel	Ref. 1
Fricative	Position not specified	1. Fricative noise spectrum 2. Vocalic formant transitions	Ref. 8

Note: Consonants may differ from each other by being produced by an obstruction or narrowing at different locations in the oral cavity (e.g., /b/ and /d/ and /g/).

Table 3. Cue-trading relations for manner of articulation.

Manner of Articulation	Context	Cues that Trade	Source
Stop	Between fricative and vowel	1. Closure duration and formant onset frequencies 2. Duration and amplitude contour of fricative noise and closure duration	Ref. 1
Fricative/ Affricate	Initial position in syllable	1. Rise time 2. Noise duration	Ref. 8
	Final position	1. Vocalic offset spectrum 2. Closure duration 3. Fricative noise duration	Refs. 8, 9

Note: Manner of articulation is the primary division of consonants. Stop consonants are cued by a silent gap apparent in the spectrogram. In the fricative-stop-vowel context, it is possible to produce the characteristics of a fricative followed by a silence and then by a vowel, while omitting the burst that usually characterizes the release of closure in a stop consonant. When this is done, observers still perceive a stop consonant /p/ when the silence between *s* and *lit* exceeds 70 msec (i.e., *split* is heard). An affricate is a combination of a stop and a fricative.

8.208 Pronunciation Latency and Pronunciation Time for Memorized Word Lists

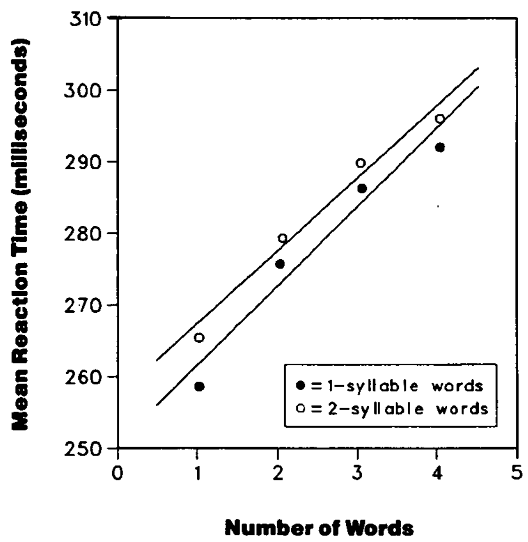

Figure 1. Time to begin speaking a list of words as a function of the number of words in the list. The lines are fitted linear functions (see text). (From Ref. 2)

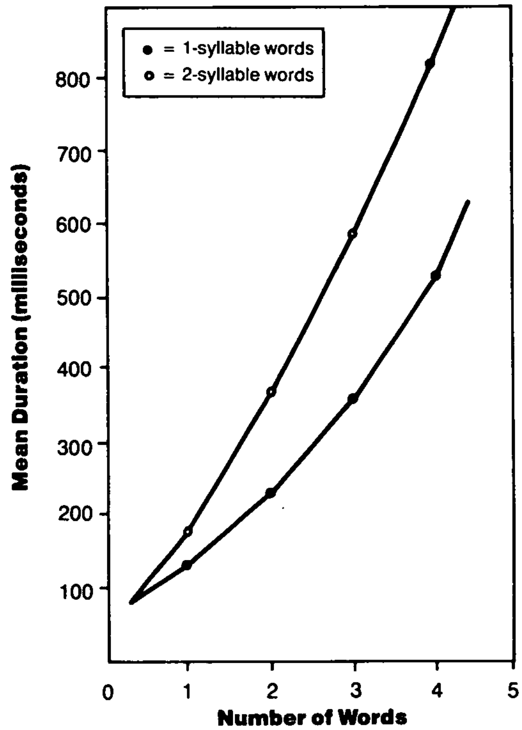

Figure 2. Duration of utterances of word lists as a function of the number of words in the lists. The lines are fitted quadratic functions (see text). (From Ref. 2)

Key Terms

Communications; motor programming; pronunciation latency; pronunciation time; reaction time; speech production

General Description

Advanced planning or motor programming of rapid movement sequences (e.g., utterance of memorized word strings) is sensitive to a hierarchy of factors, such as number of syllables, number of words, and word-group size. For example, after a warning signal, simple reaction time (RT) until the *beginning* of an utterance increases linearly with the number of words in the utterance (Fig. 1). As indicated by the slope of the function, RT is increased by 10 msec for each additional word in the utterance, whether the list is composed of one-syllable or two-syllable words. The y-intercept is ~5 msec greater for lists of two-syllable words, possibly indicating that the first word is broken into syllables before the utterance begins. This reflects a factor considered to be at a lower level in the hierarchy. At a higher level, insertion of words without primary stress (such as *and* or *of*) between each of the words (nouns) in the list also affects the intercept but not the slope of the functions.

Of course, it takes longer to utter two-syllable words than one-syllable words and to utter two words rather than one word; however, the quadratic functions fit to the data for response duration accelerate as the number of words increases, indicating that longer lists are uttered at a slower rate (Fig. 2).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Subjects memorized lists of one to four one-syllable or two-syllable words; words were 72 common nouns; the first syllable of all two-syllable words was stressed and was an approximation of one of the one-syllable words on the one-syllable list (e.g., *cow-coward*, *bay-baby*)
- Lists for each day drawn from a set of nine words of each length; sets chosen so that pair members occurred on different days; three successive trials on each list
- List presented for memorization at a rate of 1 item/sec; list followed by ~4 sec delay for rehearsal and response preparation; after delay, a visual "recite" signal was presented on ~85% of trials; "recite" signal preceded by two auditory "countdown" signals at 1-sec intervals; on ~15% of trials (catch trials) "recite" signal omitted and subject did not have to respond

Experimental Procedure

- Reaction time
- Independent variables: list length, number of syllables per word
- Subject's task: memorize list of words presented visually, speak words as rapidly as possible (beginning as soon as possible after the "recite" signal)
- Instruction, feedback, scores, and cash bonuses were designed to shorten both RT and duration of the utterances
- 4 female high school students with extensive practice

Experimental Results

- Reaction time to begin reciting word lists increases as list length (number of words) increases (Fig. 1). Out of a number of similar experiments using lists of up to six words, the latency functions for this experiment only were nonlinear. Thus, in spite of the significant nonlinearity, the data were fit with the linear function $L(n) = \eta + \theta(n - 1)$ where n is the number of words in the list, $L(n)$ is reaction time, and η and θ are parameters fitted to the data by the method of least squares.
- The slopes of the RT functions for one-syllable word lists and two-syllable word lists are almost identical (a difference of 0.9 ± 1.1 msec per word); however, mean RTs are 4.5 ± 1.3 msec longer for two-syllable words than for one-syllable words across all list lengths.
- The effects of number of syllables per word and list length are additive.
- The increase in the duration of an utterance as list length increases is shown in Fig. 2. Data were fit by the quadratic function $D(n) = \alpha + \beta(n - 1) + \gamma(n - 1)^2$, where n is the number of words in the list, $D(n)$ is the duration of the utterance, and α, β, and γ are parameters determined by a least-squares fit to the data.
- The differences in the quadratic functions that describe the duration data (Fig. 2) for one- and two-syllable words are seen in the intercepts, α (122.4 versus 173.4 msec) and linear coefficients, β (91.9 versus 180.4 msec per word); the quadratic coefficients, γ, are almost identical (13.6 versus 12.0 msec per word with a difference of 1.6 ± 0.9 msec per word) and both functions accelerate with list length.

Variability

No information about variability was given for this experiment, but for a digit-reciting task, the same four subjects had RT slopes of 10.1, 9.5, 19.4, and 11.3 msec per word.

Repeatability/Comparison with Other Studies

Similar RT and duration results were obtained with lists consisting of days of the week (in sequence, repeated, and random) and the digits 1-5 in ascending order. Other experiments demonstrate that: (a) also memorizing a second short list to be recited slowly after the first list does not affect either RT or duration; (b) changing to an auditory "recite" signal does not significantly affect the slopes of the functions; and (c) using a highly variable interval between the list presentation and the "recite" signal increases the mean RTs, but has little effect on the slopes. An increase in simple RT with an increasing number of elements in a sequence of movements made with one arm is reported in Ref. 1.

Constraints

- No explanation is offered for the deviation from linearity in the RT data.
- For list lengths of more than six words, RT tends to fluctuate about an asymptotic value rather than to increase with list length in an orderly way.

Key References

1. Henry, F. M., & Rogers, E. E. (1960). Increased response latency for complicated movements and a "memory drum" theory of neuromotor reaction. *Research Quarterly of the American Association for Health, Physical Education and Recreation*, *31*, 448-458.

*2. Sternberg, S., Monsell, S., Knoll, R. L., & Wright, C. E. (1978). The latency and duration of rapid movement sequences: Comparisons of speech and typewriting. In G. E. Stelmach (Ed.), *Information processing in motor control and learning*. New York: Academic Press.

Cross References

8.209 Pronunciation latencies for words and pseudowords with typical or atypical pronunciation;

8.210 Pronunciation time for sentences: effect of practice and semantic content;

9.108 Factors affecting simple reaction time;

Handbook of perception and human performance, Ch. 27, Sect. 4.2

8.209 Pronunciation Latencies for Words and Pseudowords with Typical or Atypical Pronunciation

Key Words

Communications; motor programming; pronounceability; pronunciation latency; reaction time; reading; speech production

General Description

English words may be classified as regular words (pronounced with a typical spelling-to-sound correspondence, e.g., *beef*) or exception words (atypical correspondence, e.g., *been*). Regular words are read aloud more quickly than exception words.

Pseudowords are pronounceable but meaningless letter strings. In general, words are read aloud more quickly than pseudowords. If pseudowords are constructed by replacing the initial consonant of a word, one may speak of regular and exception pseudowords, based on the class of word that was altered. Regular pseudowords are pronounced more quickly than exception pseudowords.

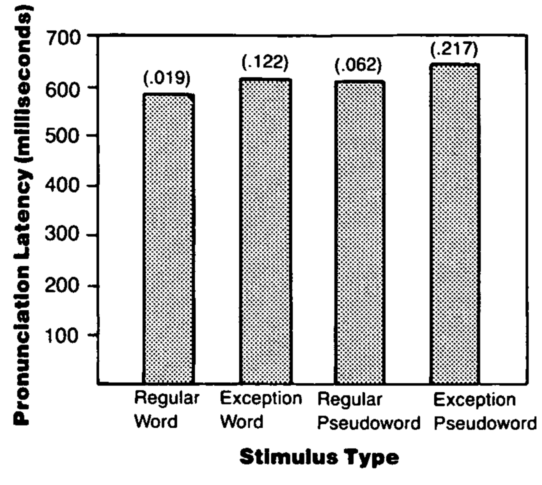

Figure 1. Pronunciation latency for singly presented words and pseudowords as a function of pronunciation regularity. Regular words show a spelling-to-sound correspondence typical for English words; exception words show an atypical correspondence. Regular and exception pseudowords are constructed to be analogous to regular and exception words. Error rates are shown above bars. Latencies are 598, 618, 617, and 646 msec, respectively, for regular words, exception words, regular pseudowords, and exception pseudowords. (Data from Ref. 2)

Applications

Design of neologisms (newly coined words or expressions, often criticized as being unrefined) and acronyms; diagnosis of reading deficiencies related to knowledge of orthography (rules for legal sequencing of letters) and development of materials for teaching orthography.

Methods

Test Conditions

- 43 monosyllabic exception words (e.g., *deaf*) and 43 regular words chosen so that, where possible, the word pairs differed only in the terminal consonant (e.g., *dean*, *deaf*); 86 pseudowords were constructed from regular and exception examples by changing initial consonant (e.g., *hean*, *heaf*)
- Words presented on display screen of PDP 11/45 computer (white letters on dark background), which controlled stimulus presentation and recorded pronunciation latency; words presented for 1 sec
- So that randomly ordered stimuli differing in a single letter were never consecutively presented, 172 experimental stimuli and 100 filler words were interwoven

Experimental Procedure

- Independent variables: type of stimulus (word or pseudoword), pronunciation regularity (regular or exception)
- Dependent variables: pronunciation latency, percentage of errors in pronunciation
- Observer's task: push button to view stimulus item; pronounce stimulus item into microphone as quickly as possible
- 12 observers; all native English speakers with normal speech and hearing

Experimental Results

- Words are pronounced more quickly and with fewer errors than are pseudowords ($p<0.05$).
- Regular words and pseudowords are pronounced more quickly and with fewer errors than are exception words and pseudowords ($p<0.05$).

Variability

Significance of the independent variables and interactions was determined by analysis of variance. No specific information on variability was given.

Repeatability/Comparison with Other Studies

The advantage of words over pseudowords and regular words over exception words has been shown previously (Refs. 1, 2, 3). However, the size of the advantage of regular words over exception words depends on the familiarity of the words and the recency with which words with similar patterns of spelling-to-sound translation have been pronounced. The advantage of regular pseudowords over exception pseudowords was tested in this study and was replicated in a second experiment reported in the study.

Constraints

- Other factors affect the latency to pronounce a word, particularly how frequently a word is used in the language. High-frequency words are pronounced more quickly. Exception words are generally among the more frequently used words of the language, but the magnitude of this frequency effect is less than that of the regularity effect (Ref. 2).
- Among regular words, a word will be more quickly pronounced if there are not exception words in the language that closely resemble it in spelling.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Forster, K. I., & Chambers, S. M. (1973). Lexical access and naming time. *Journal of Verbal Learning and Verbal Behavior, 12*, 627-635.

*2. Glushko, R. J. (1979). The organization and activation of orthographic knowledge in reading aloud. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 674-691.

3. Perfetti, C. A., & Hogaboam, T. (1975). Relationship between single word decoding and reading comprehension skill. *Journal of Educational Psychology, 67*, 461-469.

Cross References

8.108 Visual language processing of words and nonwords: effect of meaningfulness and pronounceability;

8.208 Pronunciation latency and pronunciation time for memorized word lists;

8.210 Pronunciation time for sentences: effect of practice and semantic content

8.210 Pronunciation Time for Sentences: Effect of Practice and Semantic Content

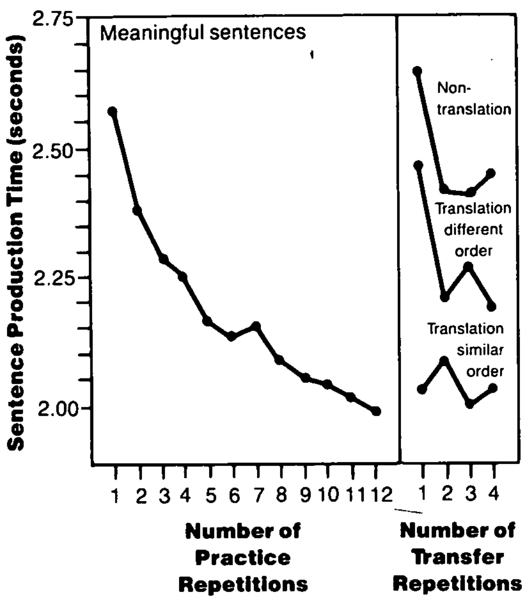

Figure 1. Mean time to produce meaningful sentences as a function of practice. Left panel shows time to produce English and German sentences in the regular task or practice sentences in the transfer task as a function of number of repetitions. Right panel shows the time to produce a transfer sentence that followed the practice sentence; transfer sentences were in a different language and were either a translation of the practice sentence with the same word order, a translation with a different word order, or a non-translation. (From Ref. 2)

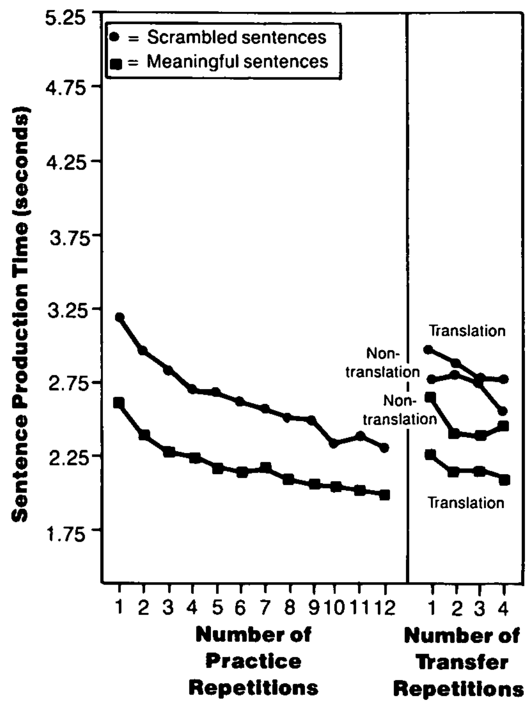

Figure 2. Mean time to produce meaningful and scrambled sentences as a function of practice. Left panel shows time to produce scrambled or nonscrambled (meaningful) practice sentences in German and English as a function of number of repetitions. Right panel shows time to produce a transfer sentence that followed the practice sentence; transfer sentences were in a different language and either were or were not a translation of the practice sentence. (From Ref. 2)

Key Terms

Priming; pronunciation time; speech production; speech rate

General Description

The time required to pronounce a sentence decreases with the number of repetitions of the sentence. For translations between two languages (e.g., English and German), practicing a meaningful sentence in one of the languages increases the maximal speech rate for repeating the sentence translated into the other language. The greatest gain occurs when the sentences in the two languages have similar word order. However, when identical word order is used in the two languages, but the words do not form a coherent sentence (i.e., scrambled sentences), there is no gain from having practiced in one of the languages before repeating the translation; in fact, there may even be a slight loss. This indicates that the facilitation is due to practicing sentence meaning rather than practicing words.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Stimuli were meaningful or scrambled sentences in either English or German from 14-16 syllables long; each sentence typed on an index card
- For the regular task, subject read aloud each of 12 sentences 12 times, speaking the sentence as quickly as possible; subject was told whether sentence would be English or German
- For the transfer tasks, subject read aloud a sentence in one language (the practice sentence) 12 times, speaking as quickly as possible, then read aloud a sentence in the other language (the transfer sentence), again speaking as quickly as possible
- For transfer tasks with meaningful sentences, the second (transfer) sentence either (1) had the same meaning as (i.e., was a translation of) the first (practice) sentence or was a completely unrelated sentence (non-translation); (2) the second sentence had the same meaning as the first but had either the same or different word order
- For transfer tasks with scrambled sentences, the second (transfer) sentence either was a translation of the first (practice) sentence or a completely unrelated sentence

Experimental Procedure

- Within-subjects design
- Independent variables: amount of practice (repetition number for sentence), translation versus non-translation, same or different word order, meaningful versus scrambled sentences
- Dependent variable: pronunciation time for sentences
- Subject's task: read sentences aloud as quickly as possible for a specified number of repetitions
- 12 German-English bilingual university students who had spoken second language for an average of 6 yr

Experimental Results

- Practice in saying either a meaningful or a scrambled sentence increases the speed of pronunciation until performance reaches an asymptote.
- When a meaningful sentence in one language is followed by an unrelated sentence in another language, the second sentence is pronounced at the same speed as the first sentence. When the second sentence is a translation of the first, it is produced faster ($p < 0.05$); this advantage is greatest when the first and second sentences have similar word order ($p < 0.05$) (Fig. 1).
- For scrambled sentences, translated and unrelated second sentences are pronounced at approximately equal rates (Fig. 2).

Variability

Two-tailed, sign-rank tests were used to test significance of results. No information on variability was given.

Repeatability/Comparison with Other Studies

Improvement of performance with practice is a common finding for motor skills (CRef. 4.201).

Key References

1. MacKay, D. G. (1981). The problem of mental practice. *Journal of Motor Behavior, 13*, 274-285.

*2. MacKay, D. G., & Bowman, R. W., Jr. (1969). On producing the meaning in sentences. *American Journal of Psychology, 82*, 23-39.

Cross References

4.201 Power law of practice;

8.208 Pronunciation latency and pronunciation time for memorized word lists;

8.209 Pronunciation latencies for words and pseudowords with typical or atypical pronunciation

8.301 Effect of Type of Test Material on Speech Intelligibility

Key Terms

Communications; word length; word stress pattern

General Description

Speech intelligibility is greater for some types of test materials than for others, presumably because of their greater redundancy. For example, sentences are more intelligible than isolated words. Spondees (two-syllable words with equal stress on both syllables) are more intelligible than randomly selected two-syllable words, which in turn are more intelligible than phonetically balanced one-syllable words. Speech intelligibility thresholds vary from a relative intensity of 5-15 dB depending on number of syllables, phonetic content, and stress pattern.

Methods

Test Conditions

- Two lists of 42 disyllabic spondees (i.e., words with both syllables accented, such as *blackbird, railroad*); each list recorded in six scrambled versions; each divided into seven groups of six words, each group recorded 4 dB lower than previous group; words separated by 6-sec intervals; words preceded by carrier phrase "Number one," "Number two," etc., recorded at highest intensity; one list of 50 unselected (i.e., randomly chosen) disyllables read in re-scrambled forms at different intensity levels; three to five lists of 50 phonetically balanced monosyllables (phonetically balanced word lists are those in which the frequency of occurrence of various **phonemes** is proportional to their occurrence in everyday English)
- Eight lists of sentences comprising short questions that could be answered by one word; each list had 28 items divided into seven groups of four items, each group recorded 4 dB lower than previous group

Experimental Procedure

- Descending method of limits
- Independent variables: type of test material, intensity of presentation
- Dependent variable: percentage of items heard correctly at each intensity level: intelligibility threshold, defined as intensity level at which responses are 50% correct
- Subject's task: for word tests, write down word following carrier phrase; for sentence test, answer questions asked by sentence
- 18 subjects with normal hearing (10 in spondee condition; four in unselected disyllable condition; four in phonetically balanced monosyllable condition)

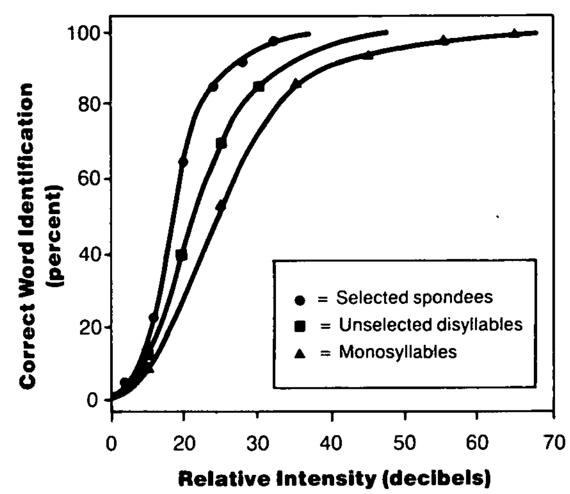

Figure 1. Intelligibility of different types of test materials for normal listeners. Percentage of words heard correctly at each relative intensity level is given for spondees (two-syllable words with equal accent on both syllables), randomly selected two-syllable words, and phonetically balanced one-syllable words. (From Ref. 1)

Experimental Results

- Spondees are more intelligible than unselected disyllables, which in turn are more intelligible than phonetically balanced monosyllables.
- Threshold for sentences (relative intensity for 50% correct responses) is lower than the threshold for single syllable words (data not shown).
- Thresholds vary from 5-15 dB, depending on the test materials.

Variability

Standard error of measurement for spondees was 2 dB for 30 normal subjects tested under very favorable laboratory conditions and 2.4 dB for 37 normal subjects under less favorable conditions; similar results are obtained for hard-of-hearing subjects.

Constraints

- Speech intelligibility is influenced by many factors: the presence of noise, the presence of distractors, visual cues, and hearing loss (CRefs. 8.302, 8.303).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Hudgins, C. V., Hawkins, T. E., Karlin, J. E., & Stevens, S. S. (1947). The development of recorded auditory tests for measuring hearing loss for speech. *Laryngoscope, 57*, 57-89.

Cross References

8.302 Effect of filtering on speech intelligibility;

8.303 Effects of visual cues on speech intelligibility;

8.304 Factors affecting the intelligibility of speech in noise;

8.317 Methods of predicting speech intelligibility

8.302 Effect of Filtering on Speech Intelligibility

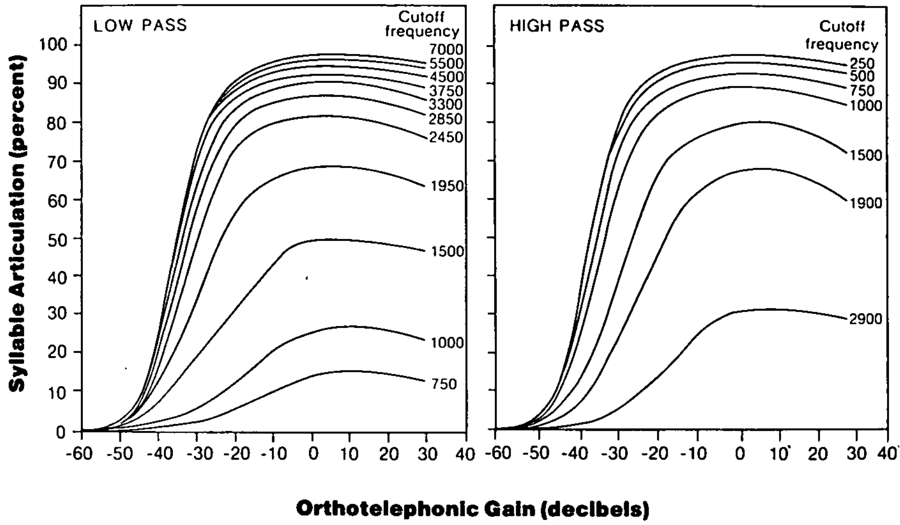

Figure 1. Intelligibility of filtered speech. Percentage of nonsense syllables heard correctly is shown as a function of orthotelephonic gain and filter cutoff frequency for low-pass and high-pass filtering. (From Ref. 1)

Key Terms

Communications; orthotelephonic gain; sound frequency; speech filtering

General Description

The intelligibility of low-pass- or high-pass-filtered speech varies with the cutoff frequency of the filtering. Greatest decrements in performance occur when frequency bands between ~750-3000 Hz are removed. Optimum perception occurs at an orthotelephonic gain of + 10 dB for all filter bandwidths (orthotelephonic gain is the intensity of the signal relative to the sound pressure level of normal conversation in a free-field 1 m in front of the speaker, which is ~65 dB).

Methods

Test Conditions

- Test materials were meaningless syllables consisting of consonant-vowel-consonant combinations, composed of sounds normally used in conversation, spoken by male and female voices
- Test syllables were either low-pass filtered or high-pass filtered prior to presentation; low-pass filters had cutoff frequencies of 750-7000 Hz; high-pass filters had cutoff frequencies from 250-2900 Hz
- Orthotelephonic gain varied from −60 to +30 dB, in 10-dB increments
- No other details of test conditions given

Experimental Procedure

- Independent variables: orthotelephonic gain, type of filtering and filter cutoff frequency
- Dependent variable: percentage of correct syllable articulation (the percentage of syllables for which all three sounds were perceived correctly)
- Subject's task: repeat spoken syllables
- Number of subjects not reported

Experimental Results

- Perception of speech is most degraded by high-pass or low-pass filtering with a cutoff frequency in the 750-3000-Hz range.
- Optimum speech perception occurs at an orthotelephonic gain of + 10 dB, regardless of the filters used.
- Curves for low-pass and high-pass filtering at an orthotelephonic gain of + 10 dB intersect at 68% correct syllable articulation, corresponding to an articulation index of 0.50 (or one-half the optimal level of received speech for the given transmission system with full-band passing) (Fig. 2). Curves for the + 10 dB condition intersect at ~1900 Hz; this means that, for this particular transmission system, half of the articulation level for full-band speech is carried by frequencies below ~1900 Hz and half by frequencies above this value.
- Low- and high-pass filters' curves at an orthotelephonic gain of −30.6 intersect at 25%, corresponding to an articulation index of 0.25 (Fig. 2).

Variability

No information on variability was given.

Constraints

- Values obtained from the syllable articulation test depend on the skill and experience of the listener.
- Unlike the articulation index, syllable articulation is not an additive measure of the importance of the contributions made by the speech components in different frequency regions.
- Speech intelligibility is influenced by many factors, including the presence of noise, the type of test material, the presence of visual cues, and hearing loss (CRefs. 8.301, 8.303).

Key References

*1. French, N. R., & Steinberg, J. C. (1947). Factors governing the intelligibility of speech sounds. *Journal of the Acoustical Society of America*, *19*, 90-119.

Cross References

8.301 Effect of type of test material on speech intelligibility;

8.303 Effects of visual cues on speech intelligibility;

8.307 Noise masking of speech: effect of filtering, listening conditions, relative signal intensity, and type of mask;

8.317 Methods of predicting speech intelligibility;

Handbook of perception and human performance, Ch. 26, Sect. 4.1

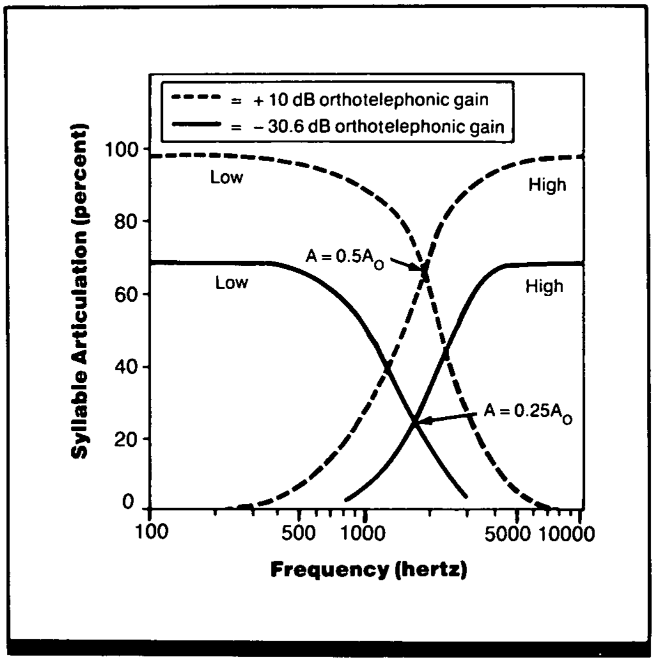

Figure 2. Percentage of nonsense syllables heard correctly under low-pass and high-pass filtering as a function of filter cutoff frequency. Curves are shown for orthotelephonic gain of +10 dB and −30.6 dB. *A* is the percentage correct syllable articulation under the given filter conditions; A_0 is the optimal articulation level for the transmission system with full-band passing. (From Ref. 1)

8.303 Effect of Visual Cues on Speech Intelligibility

Key Terms

Communications, lip reading; noise masking; signal-to-noise ratio

General Description

Lip reading can raise unintelligible speech to an intelligible level and can alter the identification of intelligible speech if visual and auditory information are incompatible. Combining unintelligible lip-reading cues with unintelligible speech can produce an intelligible signal.

Applications

In poor listening environments, intelligibility may be increased by providing visual cues. Asynchronous audiovisual displays may substantially reduce intelligibility; speech may be transmitted at unintelligible levels (as for codes) and later recombined with visual information to restore intelligibility.

Methods

Methodological details are given in Table 1.

Experimental Results

- The presence of visual (lip-reading) information substantially enhances speech intelligibility, especially at low signal-to-noise ratios (Studies 1, 2).
- Combining unintelligible visual information (0% correct word recognition from visual information alone) with relatively unintelligible audio information (50% correct word recognition from audio information alone) produces significant improvement in speech intelligibility; better visual information increases the improvement (Studies 1, 2).
- The perception of syllables reliably identified from auditory information alone may be altered by presentation of conflicting visual information, even when subjects are instructed to attend to audio information only (Study 3). For example, a syllable reliably identified as /da/ is frequently reported as /ba/ when the sound for /da/ is accompanied by a visual cue consisting of the lip movements for /ba/ (Fig. 3). Similar biasing effects are found for vowel sounds (data not shown).

Variability

Bars in Fig. 1 indicate ± 1 standard deviation. Audition-only performance was found to be less among subjects than was audio-visual recognition. Increased variability in audio-visual scores at poorer S/N ratios was attributed to differences in lip reading skill among untrained subjects. (Ref. 1).

Repeatability/Comparison with Other Studies

Effects of visual speech cues have been replicated across a large number of subjects, laboratories, and speech stimuli. Audio information is less useful in the absence of good video information for monosyllables than for disyllables, but good video information is equally useful for all syllable lengths (Ref. 2).

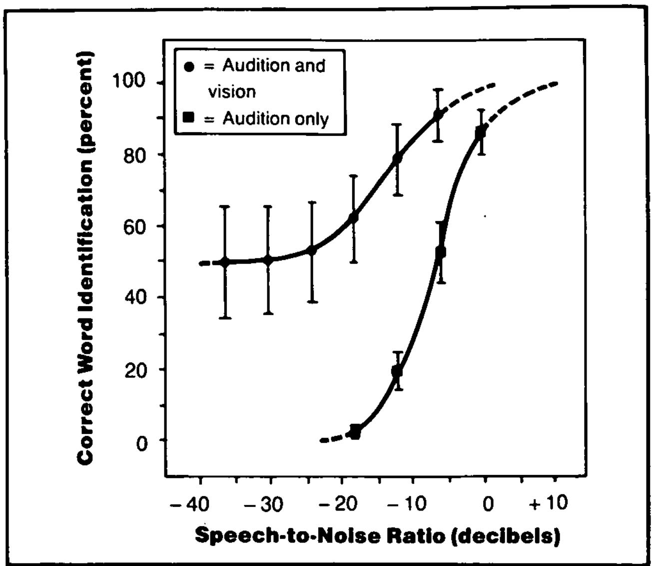

Figure 1. Accuracy in identifying two-syllable words presented in noise at varying signal-to-noise ratios (Study 1). Words were heard only or were presented with lip-reading cues as well. (From Ref. 1)

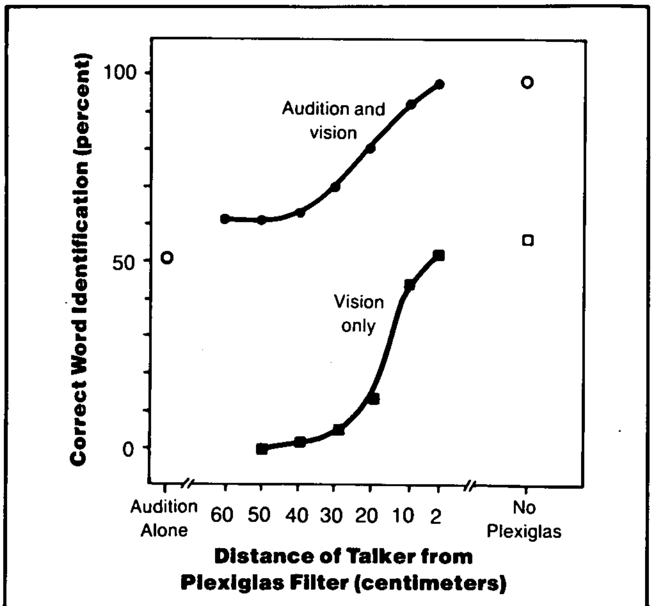

Figure 2. Identification accuracy for spoken words with degraded auditory and visual (lip-reading) information (Study 2). Spoken words were filtered to reduce intelligibility to levels approximating severe hearing loss; speaker was viewed through a rough-surfaced Plexiglas filter that blurred view of speaker's lips. Word intelligibility is shown as a function of the distance of the speaker from the Plexiglas filter when the speaker was seen only and when the view of the speaker was accompanied by a filtered audio presentation of the words as the speaker pronounced them. The intelligibility of the auditory information alone and of the lip-reading information alone without visual filtering is also shown. (From Ref. 3)

Constraints

- Many factors, such as the presence of noise, the type of test material, and speech filtering, affect the intelligibility of speech (CRefs. 8.301, 8.302).

Key References

*1. Erber, N. P. (1969). Interaction of audition and vision in the recognition of oral speech stimuli. *Journal of Speech and Hearing Research, 12,* 423-425.

2. Erber, N. P. (1975). Auditory-visual perception of speech. *Journal of Speech and Hearing Disorders, 40,* 481-492.

*3. Erber, N. P. (1979). Auditory-visual perception of speech with reduced clarity. *Journal of Speech and Hearing Research, 22,* 212-223.

*4. Massaro, D. W. & Cohen, M. M. (1983). Evaluation and integration of visual and auditory information in speech perception. *Journal of Experimental Psychology: Human Perception and Performance, 9,* 753-771.

*5. Summerfield, Q., & McGrath, M. (1984). Detection and resolution of audiovisual incompatibility in the perception of vowels. *Quarterly Journal of Experimental Psychology, 36A,* 51-74.

Cross References

8.301 Effect of type of test material on speech intelligibility;

8.302 Effect of filtering on speech intelligibility;

8.304 Factors affecting the intelligibility of speech in noise

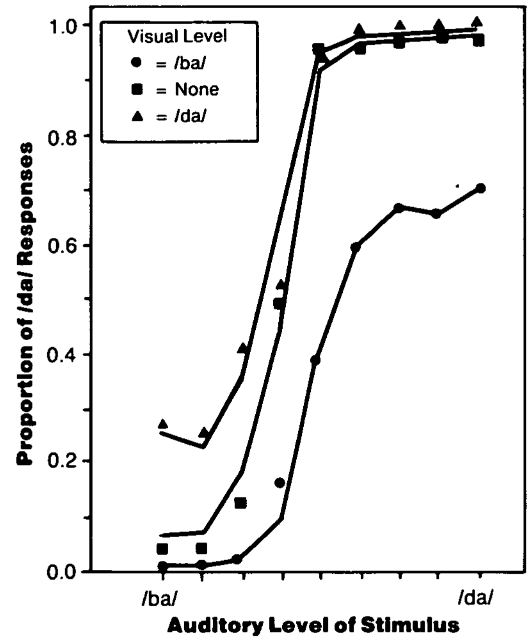

Figure 3. Perception of speech sounds with consistent and inconsistent visual (lip-reading) cues (Study 3). Subjects heard a synthetic speech syllable that was either /ba/ or /da/ or a sound along the continuum between these two syllables while simultaneously viewing a video display of a speaker saying /ba/ or /da/ or with lips closed (no visual cue). The proportion of trials on which each sound was heard as /da/ is shown as a function of the sound presented and the visual information provided. (From Ref. 4)

Table 1. Details of experimental methods.

	Test Conditions	Experimental Procedure
Study 1 (Ref. 1)	250 words and word pairs; broadband noise mask at signal-to-noise (S/N) ratios of −40, −30, −20, −10, 0, 10, 20, 30, or 40 dB Words presented with or without lip-reading cues	Independent variables: presence or absence of lip-reading cues; speech S/N ratio Dependent variable: word identification accuracy Subject's task: identify words heard 5 normal-hearing adult subjects
Study 2 (Ref. 3)	240 words passed through 450-Hz, low-pass filter (36 dB rolloff/octave) to simulate severe hearing loss; presented via earphones Speaker and listener in separate rooms with glass pane; speaker in clear view or behind Plexiglas (3 mm thick, rough on both sides) which blurred visibility from 20/20 (at 2 cm) to 20/600 (60 cm) at distances of 2, 10, 20, 30, 40, 50, or 60 cm Subjects heard words and saw speaker in clear or blurred view, heard words only, or saw speaker only	Independent variables: presence versus absence of auditory or visual information, visibility of lip-reading cues Dependent variable: word identification accuracy Subject's task: identify words heard, seen, or both 2 adult female subjects
Study 3 (Refs. 4, 5)	Synthetic speech stimuli comprising a continuum from /ba/ to /da/ (consonant task; Ref. 4) or /bud/ to /bad/, /bad/ to /bid/, and /bid/ to /bud/ (vowel task; Ref. 5) Videotape of speaker presenting one of the continuum endpoints or with lips closed, shown over video monitors Syllables at each location on the auditory continuum presented by loud speaker and accompanied by video display of speaker pronouncing syllable at one or the other endpoints of the continuum or with lips kept closed	Independent variables: auditory stimulus, presence or absence of visual stimulus Dependent variable: identification accuracy 6 subjects for consonant task; 12 subjects for vowel task

8.304 Factors Affecting the Intelligibility of Speech in Noise

Key Terms

Communications; frequency separation; laterality; message set; noise masking; peak clipping; redundancy; selective listening; word frequency

General Description

Intelligibility of a speech signal may be impaired by simultaneous noise presentation. The effect of the noise is lessened if its frequency band does not overlap the signals, if it is less intense, or if it is perceived as arising from a different location. Speech intelligibility may be enhanced by peak-clipping up to 90% of the signal and concentrating all the channel power into the residual center, or by increasing message redundancy semantically, syntactically, or through a smaller message set size. Older people have a harder time overcoming interference effects of noise than do younger people. The table lists a number of factors influencing the intelligibility of speech in noise, indicates the direction of the effect, and cites sources of more information.

Applications

In most speech transmission situations, listeners are not in ideal conditions and the presence of noise will affect speech intelligibility. The adverse effects may be reduced by considering message characteristics and the acoustic relationship of signal and noise.

Factor	Effect	Source
Signal-to-noise ratio	Speech intelligibility increases as the ratio of signal (speech) power to noise power increases	CRef. 8.305
Interaural differences	Presenting the speech signal to one ear and the noise to both ears, or the signal and noise to opposite ears reduces the **masking** effect of the noise	Ref. 6 CRef. 2.315
Frequency	Filtering the speech signal and noise to different frequency bands increases the intelligibility of the speech signal. Wide-band noise is more effective than narrow-band noise in masking speech. For narrow-band noise, low-frequency bands are more effective masks when the noise level is high; mid- and high-frequency bands are more effective masks when the intensity of the noise is less than that of the speech.	Ref. 8 CRefs. 7.211, 8.302, 8.306
Type of noise mask	Speech intelligibility is reduced more by voice masks than by noise masks	CRef. 8.307
Voice	Presenting speech message and distractor in different voices reduces interference	Ref. 9 CRef. 7.211
Number of voices in distractor	Noise created by mixing a number of voices interferes more with speech intelligibility than noise consisting of a single voice	Ref. 6
Message content	If speech signal and masking speech noise are on different topics, the signal is more intelligible	Ref. 9 CRef. 7.211
Message redundancy	Redundancy improves intelligibility. Noise interference is less if speech signal is composed of high-frequency-of-occurrence (as opposed to low-frequency) words, contains grammatical (as opposed to ungrammatical) sentences, is selected from a smaller (rather than larger) set of alternatives, consists of meaningful words (as opposed to nonsense syllables), or consists of disyllables with equal stress (as opposed to unselected disyllables or monosyllables)	Refs. 3, 4, 7 CRefs. 7.211, 8.301, 8.309
Location of sound sources	When speech signal and masking speech are presented from different loudspeakers, signal intelligibility increases as the distance between signal and masking speech increases	Ref. 8 CRef. 7.210

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Factor	Effect	Source
Peak clipping	Peak clipping the signal by as much as 90% and then amplifying remainder to original levels before mixing with noise improves intelligibility. Center clipping or mixing signal with noise before peak clipping destroys intelligibility	Ref. 5 CRef. 8.312, 8.313
Vocal effort	At a given signal-to-noise ratio, intelligibility is roughly the same for words spoken with normal or moderately high or low vocal effort, but declines greatly for very low or very high vocal effort (near-whisper or loud shout)	CRef. 8.310
Visual cues	The presence of visual (lip-reading) cues increases speech intelligibility	CRef. 8.303
Earplug use	At high noise levels, (>80 dB), wearing earplugs can increase the intelligibility of speech presented over a public address system	CRef. 8.316
Listener age	Older listeners have more difficulty attending to distorted, masked, or clipped speech than younger ones. Interaural phase differences are less helpful in reducing speech masking for older listeners than for younger listeners	Refs. 1, 2

Key References

1. Bergman, M. (1971). Hearing and age. *Audiology, 10,* 164-171.

2. Blumenfeld, V. G., Bergman, M., & Millner, E. (1969). Speech discrimination in an aging population. *Journal of Speech and Hearing Research, 12,* 210-217.

3. Howes, D. (1957). On the relation between the intelligibility and frequency of occurrence of English words. *Journal of the Acoustical Society of America, 29,* 296-305.

4. Hudgins, C. V., Hawkins, T. E., Karlin, J. E., & Stevens, S. S. (1947). The development of recorded auditory tests for measuring hearing loss for speech. *Laryngoscope, 57,* 57-89.

5. Licklider, J. C. R., Bindra, D., & Pollack, I. (1948). The intelligibility of rectangular speech waves. *American Journal of Psychology, 61,* 1-20.

6. Pollack, I., & Pickett, M. (1958). Stereophonic listening and speech intelligibility against voice babble. *Journal of the Acoustical Society of America, 30,* 131-133.

7. Rosenzweig, M. R., & Postman, L. (1957). Intelligibility as a function of frequency of usage. *Journal of Experimental Psychology, 54,* 412-422.

8. Spieth, W., Curtis, J. F., & Webster, J. C. (1954). Responding to one of two simultaneous messages. *Journal of the Acoustical Society of America, 26,* 391-396.

9. Treisman, A. M. (1964). Verbal cues, language, and meaning in relative attention. *American Journal of Psychology, 77,* 206-219.

Cross References

2.315 Binaural reduction of masking: effect of interaural phase differences;

7.210 Selective listening: effect of the location of sound sources;

7.211 Selective listening: effect of message frequency spectrum;

8.301 Effect of type of test material on speech intelligibility;

8.303 Effect of visual cues on speech intelligibility;

8.305 Noise masking of speech: effect of signal-to-noise ratio;

8.306 Noise masking of speech: effect of noise frequency and number of masking voices;

8.307 Noise masking of speech: effect of filtering, listening conditions, relative signal intensity, and type of mask;

8.309 Noise masking of speech: effect of message set size;

8.310 Noise masking of speech: effect of vocal force;

8.313 Noise masking of speech: effect of peak clipping;

8.316 Effect of earplugs on speech intelligibility as a function of received speech level;

8.317 Methods of predicting speech intelligibility;

8.318 Speech interference level index

8.305 Noise Masking of Speech: Effect of Signal-to-Noise Ratio

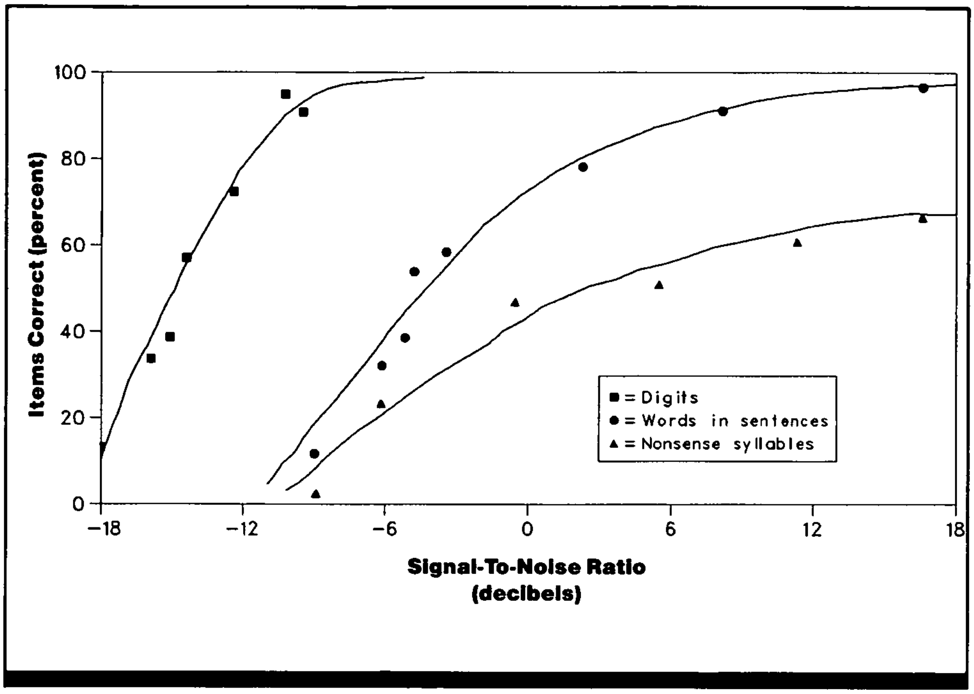

Figure 1. Intelligibility of spoken digits, sentences, and nonsense syllables presented in noise as a function of speech signal-to-noise ratio (Study 1). (From Ref. 3)

Key Terms

Communications; noise masking; signal-to-noise ratio; speech level

General Description

Recognition of spoken words increases as the ratio of signal (speech) power to noise power increases. When the noise level is between 35 and 110 dB SPL, the signal-to-noise (S/N) ratio required for speech to be just barely intelligible is constant. Intelligibility of speech decreases when the speech level exceeds 100 dB.

Methods

Test Conditions

Study 1 (Ref. 3)

- Voice inputs were single digits, sentences with five major words, or nonsense syllables
- S/N ratios varied from −18 dB to +18 dB; S/N ratio varied by keeping average voice level constant and varying noise level
- Random noise voltage with uniform spectrum between 100 and 7000 Hz
- Voice inputs were presented through earphones; overall acoustic level at the ear was ~90 dB (SPL)

Study 2 (Ref. 1)

- Voice input was continuous discourse (recordings of passages from Smith's *Wealth of Nations)*
- Monaural earphone presentation
- Input was presented under quiet conditions or at levels of white noise spaced 10 dB apart, from −46 to +34 dB re 1 mV across the earphone (sensation levels from 10-90 dB)

Study 3 (Ref. 4)

- Phonetically balanced monosyllabic word lists (those in which the frequency of occurrence of various phonemes is proportional to their occurrence in everyday English); binaural presentation via earphones; white noise; S/N ratio varied from −5 to 55 dB; speech level varied from 80-130 dB (sound levels described in terms of mean level developed by earphone, with cushion attached, on 6-cc coupler)

Experimental Procedure

Study 1

- Independent variables: type of test material, S/N ratio
- Dependent variable: percentage of items heard correctly
- Subject's task: record the word or syllable heard on a test sheet
- 2 subjects with knowledge of design and theory of the experiment

Study 2

- Method of adjustment; one to five determinations for each condition
- Independent variable: noise level
- Dependent variables: threshold of intelligibility (speech level at which the listener could obtain the meaning of almost every sentence or phrase); threshold of detectability (speech level at which the listener could detect the presence of speech ~50% of the time, but could not identify the sounds precisely)
- Subject's task: adjust the speech level until speech could just be detected or could just be understood
- 4 highly experienced subjects

Study 3

- Independent variables: speech signal level, S/N ratio
- Dependent variable: percentage of words heard correctly
- Subject's task: check each word heard against a correct checklist or write word heard
- 2 highly experienced subjects and 2-4 paid subjects chosen from a larger testing group

Experimental Results

- Recognition accuracy for speech items in noise increases as the S/N ratio increases.
- The rate at which recognition accuracy rises as S/N ratio increases depends on the nature of the test item. Rate of increase is greatest for digits, then for words in sentences, and is least for nonsense syllables.
- The S/N ratio required to reach the threshold of intelligibility and the threshold for detectability for spoken prose passages is constant when the level of the noise is between 35 and 110 dB SPL.
- Recognition accuracy for single words decreases at speech levels >100 dB regardless of the S/N ratio.

Variability

No estimates of within- or between-subject variability were reported.

Constraints

- Many factors (such as relative frequency of speech and noise, type of noise mask, speech message content, and listener's age) influence the intelligibility of speech in noise and must be considered in applying these results under different conditions (CRef. 8.304).

Key References

*1. Hawkins, J. E., Jr., & Stevens, S. S. (1952). The masking of pure tones and of speech by white noise. *Journal of the Acoustical Society of America, 22,* 6-13.

2. Licklider, J. C. R., & Miller, G. A. (1951). The perception of speech. In S. S. Stevens (Ed.), *Handbook of experimental psychology* (pp. 1040-1074). New York: Wiley.

*3. Miller, G. A., Heise, G. A., & Lichten, W. (1951). The intelligibility of speech as a function of the context of the test materials. *Journal of Experimental Psychology, 41,* 329-352.

*4. Pollack, I., & Pickett, J. M. (1958). Masking of speech by noise at high sound levels. *Journal of the Acoustical Society of America, 30,* 127-130.

5. Pollack, I., & Pickett, J. M. (1958). Stereophonic listening and speech intelligibility against voice babble. *Journal of the Acoustical Society of America, 32,* 131-133.

Cross References

8.304 Factors affecting the intelligibility of speech in noise;

8.312 Methods of reducing the masking of speech;

8.317 Methods of predicting speech intelligibility;

Handbook of perception and human performance, Ch. 26, Sects. 4.1, 4.2

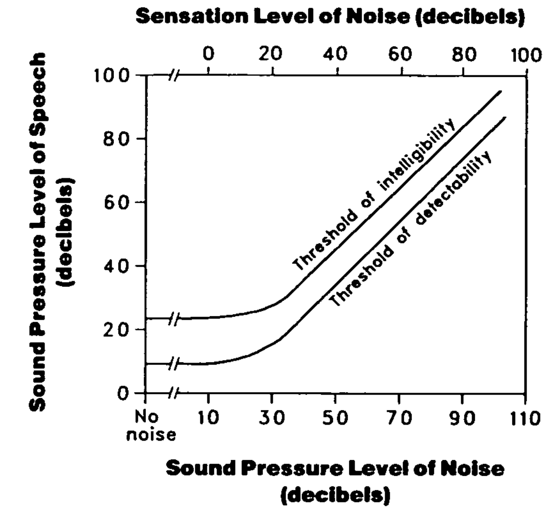

Figure 2. Threshold level for understanding and detecting spoken prose passages presented in noise as a function of noise level (Study 2). (From J. C. R. Licklider & G. A. Miller. The perception of speech, in S. S. Stevens (Ed.), *Handbook of experimental psychology.* Copyright © 1951 by John Wiley & Sons. Reprinted with permission. Modified from Ref. 1)

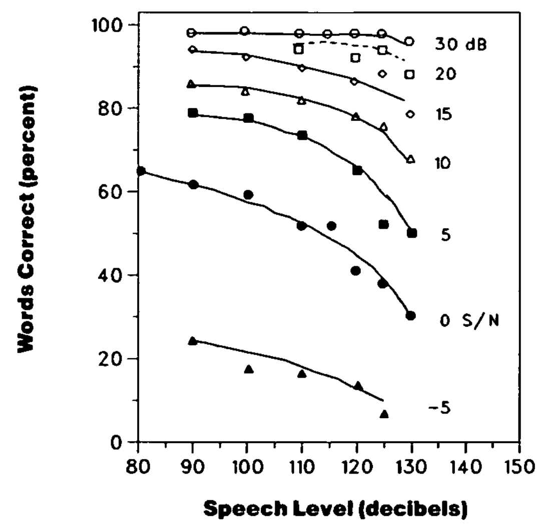

Figure 3. Intelligibility of spoken phonetically balanced monosyllabic words presented in noise as a function of speech level and speech signal-to-noise ratio (Study 3). (From Ref. 4)

8.306 Noise Masking of Speech: Effect of Noise Frequency and Number of Masking Voices

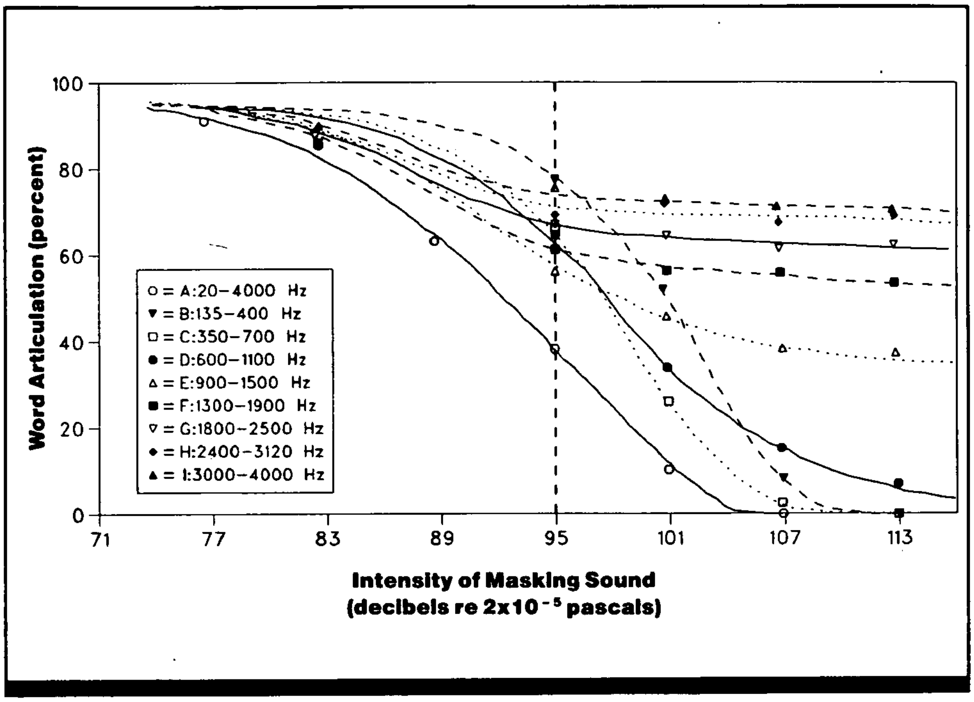

Figure 1. Percentage of words in noise heard correctly (word articulation) as a function of noise intensity and noise frequency. Level of speech was constant at 95 dB SPL. Noise was either broad-band noise (curve A) or narrow-band noise with the cutoff frequencies shown in the legend. (From Ref. 1)

Key Terms

Communications; noise masking; selective listening; signal-to-noise ratio; sound frequency

General Description

Wide-band noise (20-4000 Hz) masks speech more effectively than any low-frequency band within this spectrum of equal noise power. Midrange to high-frequency noise bands are more effective masks than low-frequency noise bands when the intensity of the noise is less than that of the speech. At high noise levels, however, the low-frequency bands are more effective masks than the high-frequency bands. In general, high-frequency noise does not mask the low-frequency components of speech, but low-frequency noise at high intensities can mask both low- and high-frequency speech components.

Multiple simultaneous voices are a more effective masking signal than a single interfering voice. The latter produces many intervals in which no masking sound is present, whereas multiple voices tend to yield a more even or continuous masking signal with fewer blank intervals.

Methods

Test Conditions

- Target vocabulary consisted of discrete words read by a male voice and phonographically recorded; binaural presentation via headphones; acoustic level constant at 95 dB SPL
- Target words presented with noise or voice mask; mask intensity varied from 77-113 dB SPL in 6-dB increments
- Masking noise was broad-band (20-4000 Hz) white noise or one of eight narrow bands of noise created by filtering wide-band noise (see Fig. 1 for noise-band cut-off frequencies); cut-off frequency defined as frequency at which system response was 6 dB below maximum in each band
- Masking voices consisted of 1 (male) or 2, 4, 6, or 8 voices (male and female) phonographically recorded; voices spoke in English or a foreign language which listeners did not know

Experimental Procedure

- Independent variables: intensity of masking sound, type of masking sound (noise or voice), frequency of masking noise, number of voices in voice mask, language of masking voice(s)
- Dependent variable: percentage of words heard correctly (word articulation)
- Subject's task: trained to develop a consistent criterion for "hearing" a word; uncovered word on checklist after it was spoken; indicated by checkmark or manual counter whether or not the word was heard correctly (author claims this procedure yields results comparable to formal articulation tests in which listeners write down what is heard without a reference list)
- 2-4 highly trained subjects for voice and noise masking

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Experimental Results

- The percentage of words heard correctly decreases as the intensity of the masking sound increases.
- Wide-band (20-4000 Hz) noise is a more effective speech mask than narrow-band noise for all intensity levels and noise frequency ranges tested.
- When the intensity of the masking noise is less than that of the speech, the higher-frequency bands (curves E, F, G, H, and I in Fig. 1) are more effective in masking the speech than the lower-frequency bands (curves B, C, and D). In contrast, when the intensity of the masking sound is greater than that of the speech, the higher-frequency bands are less effective masks than the lower-frequency bands.
- There is little or no difference in masking effectiveness between a single-voice mask and a multiple-voice mask when the speech signal-to-noise (S/N) ratio is +6, +12, or +18 dB (background noise of 89, 83, and 77 dB SPL, respectively).
- For S/N ratios of 0, −6, and −12 dB (background noise of 95, 101, and 107 dB SPL, respectively), the single-voice mask is a relatively poor masking signal, and two voices are less effective masks than four or more.
- There is no difference in the relative masking effectiveness of 4, 6, or 8 simultaneous voices.
- There is no difference in masking effectiveness for masking voices speaking English and voices speaking a language not understood by the listener (data not shown).

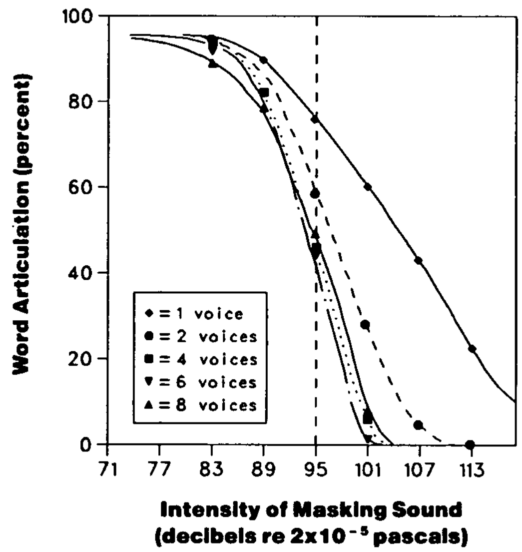

Figure 2. Percentage of words heard correctly as a function of intensity of masking sound. Mask was 1-8 voices presented simultaneously. Level of target speech was constant at 95 dB SPL. (From Ref. 1)

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

There is little difference in masking by conversational voices and masking by loud, excited voices liberally interspersed with the laughter, cheering, and improbable vocal effects characteristic of a party (Ref. 1).

Constraints

- The ability of a listener to discriminate a target voice from masking voices may be greater in free-field (non-headphone) listening.
- The scoring method is very subjective, as it uses a criterion determined by the listener. However, the overall pattern of results would probably not change with a more objective procedure.
- Many factors (such as relative frequency of speech and noise, type of noise mask, speech message content, and listener's age) influence the intelligibility of speech in noise and must be considered in applying these results under different conditions (CRef. 8.304).

Key References

*1. Miller, G. A. (1947). The masking of speech. *Psychological Bulletin, 44*, 105-129.

Cross References

8.302 Effect of filtering on speech intelligibility;

8.304 Factors affecting the intelligibility of speech in noise;

8.305 Noise masking of speech: effect of signal-to-noise ratio;

8.307 Noise masking of speech: effect of filtering, listening conditions, relative signal intensity, and type of mask;

8.312 Methods of reducing the masking of speech;

8.317 Methods of predicting speech intelligibility;

Handbook of perception and human performance, Ch. 26, Sect. 4.2

8.307 Noise Masking of Speech: Effect of Filtering, Listening Conditions, Relative Signal Intensity, and Type of Mask

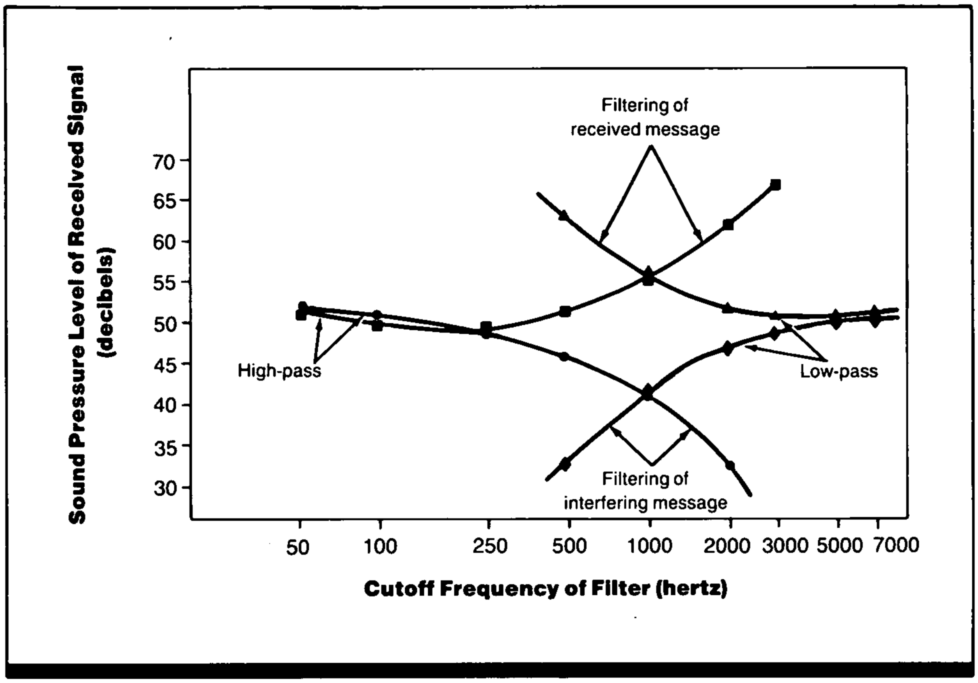

Figure 1. Intelligibility of masked speech with filtering of speech signal (received message) or masking sound (interfering message). Both speech signal and mask were prose passages presented simultaneously to one ear. Either signal or mask could be high-pass filtered or low-pass filtered. Signal level necessary to just understand the speech message is shown as a function of the cutoff frequency of the filter used. (From Ref. 1)

Key Terms

Communications; dichotic listening; lateralization; noise masking; selective listening; signal-to-noise ratio; sound frequency; speech filtering

General Description

The interference effect of two signals on one another is diminished by accentuating the differences between them. A speech message is more intelligible if the relevant signal and the distractor (mask) are presented to opposite ears or differentially filtered, if the distractor is noise rather than speech, or if the distractor is less intense than the speech signal. However, a distractor that is *more* intense than the speech signal does not have an increased masking effect. Instead, the intensity difference facilitates cueing to the relevant signal, thus offsetting the greater potential masking.

Methods

Test Conditions

- Test materials for perceptibility tests were 12 min of continuous discourse from *The Wealth of Nations* read by male voices; two passages presented together in synchrony; with intensity of one passage (mask) fixed and intensity of the other (signal) varied by subject
- Test materials for articulation tests were lists of sentences, each containing four key monosyllabic words and one key disyllabic word taken from Harvard's Psycho-Acoustic Laboratory's published list of sentences; on each trial, two sentences presented together in synchrony, preceded by different code names (Langley Base or Mitchell Field); subjects told to attend to one (signal) while ignoring the other (mask); both sentences spoken by same voice
- For filtering condition, either signal or mask was high-pass filtered or low-pass filtered before presentation
- For dichotic listening condition, both signal and distractor (mask) presented to same ear (monaural condition) or signal presented to

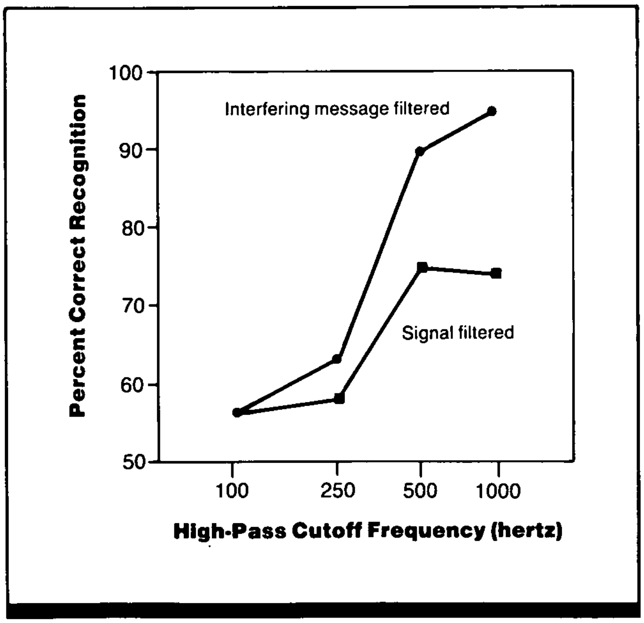

Figure 2. Intelligibility of masked speech with high-pass filtering of either speech signal or masking sound (interfering message). Both speech signal and mask were spoken sentences. Percentage of key words in sentence heard correctly is shown as a function of filter cutoff frequency. (From Ref. 1)

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one ear and distractor to the other (dichotic condition); signal was always prose passage; mask was either second prose passage presented in synchrony and read by same voice as signal, or white noise (100-4000 Hz)

- For the intensity difference condition, signal sentences and masking sentences were both presented to the same ear; the overall intensity of the mask was 58 dB SPL; the intensity of the signal was varied from − 16 dB to + 10 dB relative to mask intensity
- Stimuli for all conditions were presented via earphones

Experimental Procedure

- Independent variables: filtering (signal versus mask and high pass versus low pass), method of presentation of signal and mask (monaural versus dichotic), intensity of mask, type of mask (noise or speech)
- Dependent variables: threshold intensity of signal for understanding signal message (perceptibility test), number of key words heard correctly in sentences (articulation test)
- Subject's task: adjust signal intensity until meaning of almost every sentence and phrase could be understood with effort (perceptibility test); write designated sentence from sentence pair (articulation test)
- 3-96 subjects, depending on the experimental condition

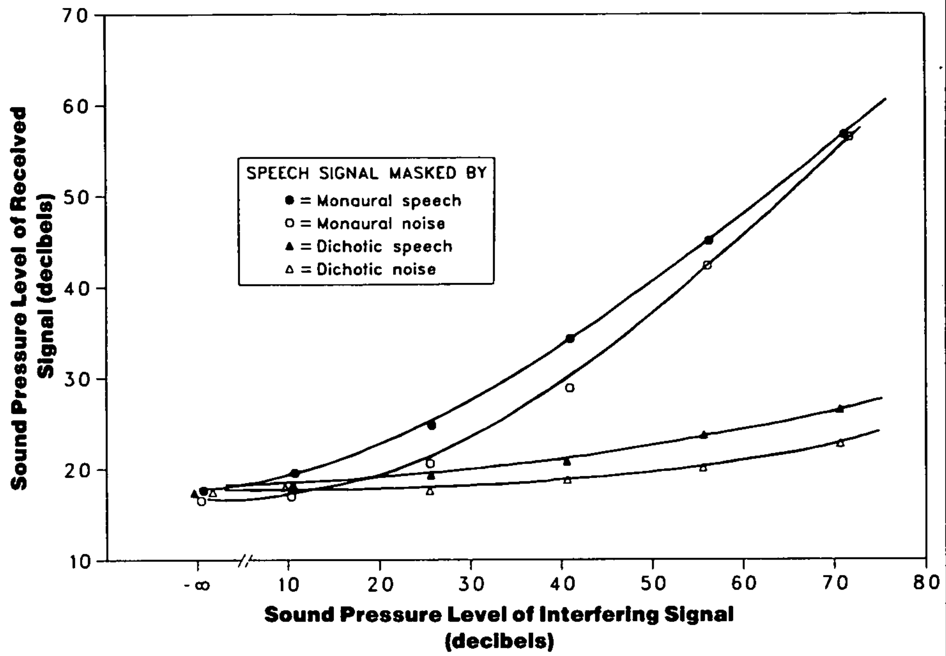

Figure 3. Intelligibility of masked speech with monaural and dichotic listening. Speech signal was prose passage; mask was either second prose passage presented simultaneously or white noise. Signal and mask presented to same ear (monaural listening) or to different ears (dichotic listening). Signal level necessary to just understand speech is shown as a function of mask level. (From Ref. 1)

Experimental Results

- The greater the filtering of the mask (distractor), the lower the intensity at which the unfiltered signal can be followed. Perceptibility threshold is increased (intelligibility is reduced) when the signal, rather than the mask, is subjected to considerable filtering (Fig. 1).
- Word articulation (word recognition accuracy) is greater when either the signal or the distractor is high-pass-filtered than when there is no filtering. Intelligibility is greater when the mask (distractor) is filtered than when the signal is filtered (Fig. 2).
- Speech intelligibility is greater when the signal is presented to one ear and the mask to the other than when both are presented to one ear (Fig. 3).
- Noise masks reduce intelligibility less than speech masks (Fig. 3).
- In general, speech intelligibility increases as the intensity of the speech signal relative to the mask increases; however, a slight discontinuity is seen, with intelligibility slightly greater when the signal intensity is slightly below mask intensity than when signal and mask intensities are equal (Fig. 4).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Replications of effects are reported within these experiments, and dichotic versus monaural effects are widely reported.

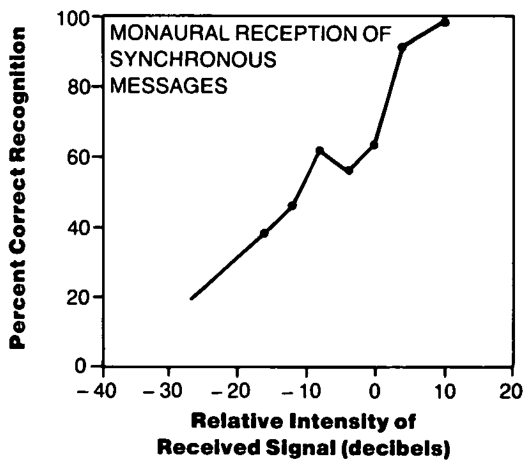

Figure 4. Intelligibility of masked speech as a function of relative intensity of the signal. Both signal and mask were sentences presented synchronously to the same ear. Mask intensity was constant and signal intensity varied as shown (where a relative intensity of 0 dB indicates that signal and mask were equal in intensity, negative values indicate that the mask was more intense than the signal, and positive values indicate that the signal was more intense than the mask). (From Ref. 1)

Constraints

• Many factors (such as relative frequency of speech and noise, type of noise mask, speech message content, and listener's age) influence the intelligibility of speech in noise and must be considered in applying these results under different conditions (CRef. 8.304).

Key References

*1. Egan, J. P., Carterette, E. C., & Thwing, E. J. (1954). Some factors affecting multi-channel listening. *Journal of the Acoustical Society of America, 26,* 774-782.

Cross References

7.209 Factors influencing performance in selective listening tasks;

8.302 Effect of filtering on speech intelligibility;

8.304 Factors affecting the intelligibility of speech in noise;

8.312 Methods of reducing the masking of speech;

8.314 Noise masking of speech: effect of interaural phase relations;

8.317 Methods of predicting speech intelligibility;

Handbook of perception and human performance, Ch. 26, Sect. 2.1

Notes

8.308 Noise Masking of Speech: Effect of Word Usage Frequency and Word Length

Key Terms

Communications: noise masking; signal-to-noise ratio; word frequency; word length

General Description

The threshold for recognizing spoken words presented in noise is lower (i.e., intelligibility is greater) for frequently used words than for rarely used words. Recognition threshold is also lower for long words than for short words.

Methods

Methodological details are given in Table 1.

Experimental Results

- For monosyllabic words presented in noise, the word recognition threshold decreases (intelligibility increases) as the usage frequency of the word increases (Fig. 1).
- For words of a constant length, the signal-to-noise ratio necessary to achieve a given level of word-recognition performance decreases as word frequency increases (Fig. 2).
- For words of a given usage frequency, the signal-to-noise ratio necessary to achieve a given level of recognition performance decreases as word length increases (Fig. 2).

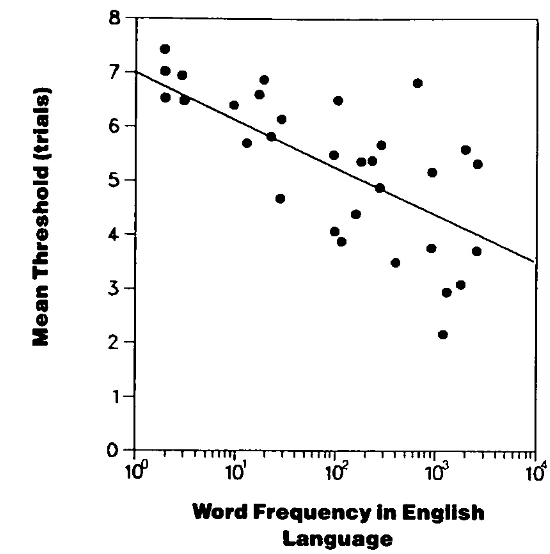

Figure 1. Mean number of presentation trials required to correctly recognize words heard in noise as a function of word frequency in the English language (Study 1). (From Ref. 2)

Table 1. Details of experimental methods.

Test Conditions	Experimental Procedure
Study 1 (Ref. 2)	
Word frequency (estimation of how often a word is used in written English) obtained from study of 4,500,000 words of text from 1929-1938 issues of five magazines with largest circulation at the time; word frequency denotes number of occurrences in this word count, rather than ratio of that number to total number of occurrences 32 monosyllabic words with usage frequencies of 1-3, 10-33, 100-330, or 1000-3300 in written English, arranged in seven different randomly ordered lists; spoken in the context "You will write—" Target words masked by **white noise** at signal-to-noise ratios of −12, −8, −4, 0, +4, or +8 dB, respectively, for first six lists and with no noise mask for seventh list A recording of a male speaker was used to present words (1 word per 10 sec) with 30-sec delay between lists	Lists presented in order of increasing signal-to-noise ratio Independent variables: word frequency, signal-to-noise ratio Dependent variables: detection threshold, defined as the number of the trial (1-7) on which word first reported correctly; number of words recalled at each word frequency Subject's task: immediately after word presented, write down all or part of it; after all lists presented, recall in writing (5 min) as many words as possible Subjects: 109 undergraduates, 87 of whom reported English as their native language, 12 another language, and 10 both English and another language
Study 2 (Ref. 1)	
282 words with usage frequencies of 1-200,000 in a sample of 4.5 million words of written English and lengths of 1, 3, 5, 7, 9, 11, 13, 15, 17, 19, and 21 letters; words divided into 4 groups of ~70 words each Target words masked with wide-spectrum noise (50-20,000 Hz) at signal-to-noise ratios of −12, −9, −6, 0, +6, +9, +12, and +20 dB; overall sound pressure level of noise held constant 80 dB sound pressure level (SPL) Words presented (1 word per 10 sec) through headphones by a male speaker preceded by 2.5-sec 1000 Hz warning tone	Signal-to-noise ratios presented in increasing order Independent variables: word frequency, word length, signal-to-noise ratio Dependent variable: detection threshold, defined as signal-to-noise ratio at which word first reported correctly Subject's task: write word immediately after word presented Subjects: 5 undergraduates, highly practiced

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• Word recall is better for better identified words (i.e., words more often recognized) (data not shown).
• Word recall is worse for poorly identified high-frequency words than for low-frequency words, even when identification rate for the high-frequency words is greater than for the low-frequency words.

Repeatability/Comparison with Other Studies

Study 2 obtained similar results for French words (Ref. 1).

Constraints

• Results apply only to words presented without a normal context, such as a sentence or paragraph. The effect is likely to disappear in contexts that narrow the word possibilities.

• Many factors (such as the type of noise mask, relative sound frequency of the mask, and listener's age) influence the intelligibility of speech in noise and must be considered in applying the results under different conditions (CRef. 8.304).

Key References

*1. Howes, D. (1957). On the relation between the intelligibility and frequency of occurrence of English words. *Journal of the Acoustical Society of America, 29,* 296-305.

*2. Rosenzweig, M. R., & Postman, L. (1957). Intelligibility as a function of frequency of usage. *Journal of Experimental Psychology, 54,* 412-422.

Cross References

8.301 Effect of type of test material on speech intelligibility;

8.304 Factors affecting the intelligibility of speech in noise;

8.309 Noise masking of speech: effect of message set size;

8.312 Methods of reducing the masking of speech;

8.317 Methods of predicting speech intelligibility;

Handbook of perception and human performance, Ch. 26, Sect. 4.2

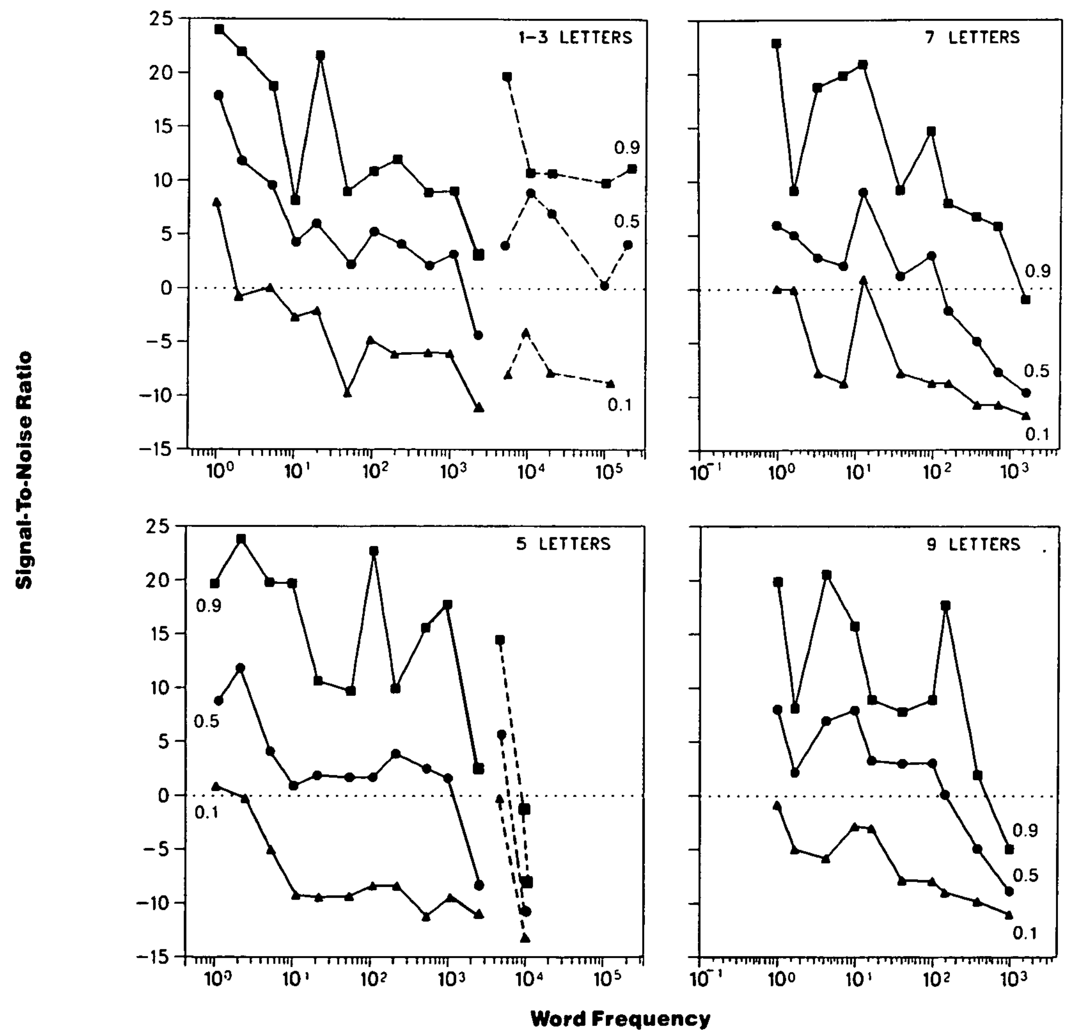

Figure 2. Signal-to-noise ratio (in decibels) required to achieve criterion performance in recognizing words presented in noise as a function of word frequency and word length (Study 2). The criterion performance was 0.1 (triangles), 0.5 (circles), or 0.9 (squares) of the items correctly recognized. Points for word frequencies ≥5000 are connected by broken lines. (From Ref. 1)

8.309 Noise Masking of Speech: Effect of Message Set Size

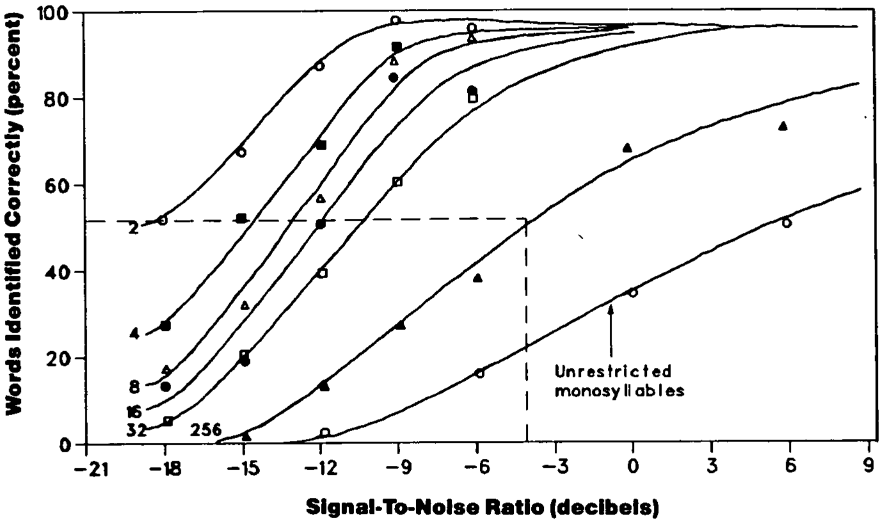

Figure 1. Intelligibility of monosyllablic words presented in noise as a function of signal-to-noise (S/N) ratio for seven vocabulary sizes. Numbers on curves indicate the number of words in the vocabulary set. Dashed lines mark S/N ratio for 50% correct word identification. (From Ref. 1)

Key Terms

Communications; message set size; noise masking; signal-to-noise ratio

General Description

Speech presented in noise is more intelligible if the number of words in the vocabulary tested is small. A higher signal-to-noise (S/N) ratio is required to correctly identify words drawn from a larger message set. These results suggest that in noisy environments communication accuracy will be enhanced by using a small vocabulary set and standardized communication procedures.

Methods

Test Conditions

- Binaural presentation via headphones
- Target vocabulary (message set) of 2, 4, 8, 16, 32, 256, or an unrestricted number of monosyllabic words; target words embedded in standardized carrier sentence ("You will write —"); acoustic level constant at 90 dB sound pressure level (SPL)
- Broadband (100-7000 Hz) random noise; variable acoustic level to yield S/N ratios of −21 to +18 dB

Experimental Procedure

- Forced-choice identification
- Independent variables: S/N ratio, size of target set
- Dependent variable: percentage of words correctly identified
- Subject's task: for restricted vocabularies, study list of alternatives prior to testing; place checkmark on list next to item heard; for unrestricted monosyllables, record word heard
- 2 highly practiced subjects

Experimental Results

- For a given S/N ratio, word recognition accuracy improves as the number of possible alternatives decreases (Fig. 1).
- Word recognition accuracy improves as the S/N ratio increases. The dashed line in Fig. 1 indicates that the 50% threshold for the 256-word vocabulary set is a S/N ratio of −4 dB. (The data shown in Fig. 1 are not corrected for chance guessing.)

Variability

No information on variability was given.

Constraints

• Many factors (such as relative frequency of speech and noise, type of noise mask, speech message content, and listener's age) influence the intelligibility of speech in noise and must be considered in applying these results under different conditions (CRef. 8.304).

Key References

*1. Miller, G. A., Heise, G. A., & Lichten, W. (1951). The intelligibility of speech as a function of the context of the test materials. *Journal of Experimental Psychology, 41*, 329-335.

Cross References

8.304 Factors affecting the intelligibility of speech in noise;

8.305 Noise masking of speech: effect of signal-to-noise ratio;

8.308 Noise masking of speech: effect of word usage frequency and word length;

8.312 Methods of reducing the masking of speech;

8.317 Methods of predicting speech intelligibility;

Handbook of perception and human performance, Ch. 26, Sect. 4.2

8.310 Noise Masking of Speech: Effect of Vocal Force

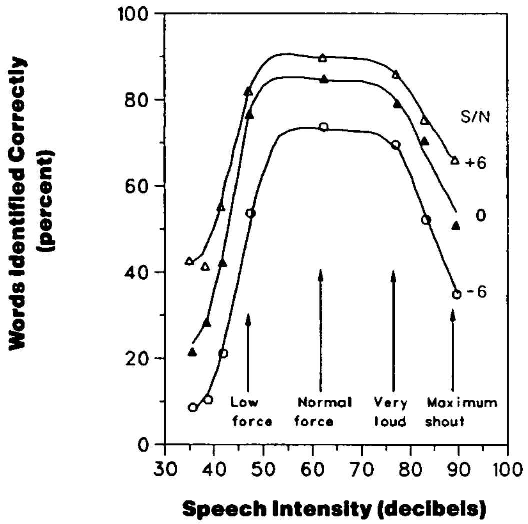

Figure 1. Intelligibility of monosyllabic words presented in noise as a function of vocal force (speech intensity) for three signal-to-noise (S/N) ratios. (From Ref. 1)

Key Terms

Communications; noise masking; signal-to-noise ratio; speech level; vocal effort

General Description

For noise-masked speech presented at a given signal-to-noise (S/N) ratio, the greatest number of words are understood if the speaker exerts only a moderate vocal effort. Intelligibility markedly decreases for a very weak voice (whisper) or a very heavy shout if the S/N ratio is held constant.

Methods

Test Conditions

- Target vocabulary contained 500 English monosyllables drawn from the Harvard PB Word Lists (word lists in which the frequency of occurrence of various phonemes is proportional to their occurrence in everyday English) and grouped into 25 word lists; lists phonographically recorded at 8 levels of vocal effort ranging from 36-90 dB measured 1 m from the lips (36 dB is the lowest level that could be attained while still **voicing** each vowel, 90 dB is the maximum level that could be maintained without producing painful voice fatigue); each word read following a carrier sentence
- Speech recordings mixed electrically with flat-spectrum noise of constant 70-dB sound pressure level (SPL) to yield S/N ratios of −6, 0, and +6 dB; stimuli played back via loudspeakers
- Each subject read word lists and then listened to recordings of other subjects' reading lists; order of presentation of talkers, levels of vocal effort, and S/N ratios randomized

Experimental Procedure

- Independent variables: vocal effort (intensity), S/N ratio
- Dependent variable: percentage of words heard correctly (word articulation)
- Subject's task: read words at eight levels of vocal effort; write down words heard in recordings of word lists and score own responses
- 6 male subjects, 5 of whom were also speakers; subjects familiarized with test words and with hearing them in noise before testing began

Experimental Results

- At each of the three S/N ratios tested, recognition accuracy for one-syllable words spoken in a "low voice" (recorded at 55 dB) or a "very loud" voice (recorded at 78 dB) remains within 5% of the performance for words spoken in a "normal voice" (recorded at 63 dB).
- At these three S/N ratios, speech intelligibility was degraded for words spoken with both the low and high extremes of vocal effort.
- An analysis of errors for different parts of the syllables indicates that shouting degrades the intelligibility of the initial and final parts of the syllable, while weak vocal effort

degrades the intelligibility of all parts of the syllable (data not shown).

Variability

No information on variability was reported.

Constraints

- S/N ratio does not normally remain constant as vocal effort increases; study does not address issue of the extent to which shouting in a noisy environment increases intelligibility as compared to lesser vocal efforts, a more realistic situation.
- Many factors (such as relative frequency of speech and noise, type of noise mask, speech message content, and listener's age) influence the intelligibility of speech in noise and must be considered in applying these results under different conditions (CRef. 8.304).

Key References

*1. Pickett, J. M. (1956). Effects of vocal force on the intelligibility of speech sounds. *Journal of the Acoustical Society of America, 28,* 902-905.

Cross References

8.304 Factors affecting the intelligibility of speech in noise;

8.312 Methods of reducing the masking of speech;

8.313 Noise masking of speech: effect of peak clipping;

8.317 Methods of predicting speech intelligibility;

Handbook of perception and human performance, Ch. 26, Sect. 5.2

8.311 Noise Masking of Speech: Effect on Speech Recall

Key Terms

Noise masking of speech; speech intelligibility; verbal recall

General Description

Recall of correctly perceived speech signals is impaired if the signals are presented in noise or follow other signals presented in noise.

Methods

Methodological details are given in Table 1.

Table 1. Details of experimental methods.

Test Conditions	Experimental Procedure
Study 1 (Ref. 1)	
40 lists of eight digits randomly ordered without repetition, spoken at rate of 1 digit/sec with 10-sec pauses between lists; presented through loudspeakers Noise added by re-recording tape through a simulated telephone link incorporating a Modulated Noise Reference Unit (MNRU), adding noise (0-3500 Hz) to signal in direct proportion to speech amplitude; signal-to-noise ratio of 0 dB in noise condition Half of the subjects transcribed list as presented with or without noise; half recalled lists in order after lists completely presented with or without noise Condition appropriately counterbalanced	Method of immediate or serial recall Independent variables: noise (presence or absence), type of recall (immediate or serial) Dependent variable: percentage of digits correctly recalled (lists were scored as correctly repeated or recalled only if digits given in correct order of presentation) Subject's task: transcribe signal as presented or recall list in order after completely presented 36 male and 44 female subjects, aged 26-68 yrs (mean of 47.2 yrs)
Study 2 (Ref. 1)	
56 lists, each containing eight different digits, selected from random number table; spoken at rate of 1 digit/sec in two groups of four digits, with 2-sec pause between groups and 10-sec pause between lists; presented through loudspeakers Lists re-recorded through a simulated telephone link incorporating an MNRU, adding noise (0-3500 Hz) to group 1 or group 2 in direct proportion to speech amplitude; signal-to-noise ratio of 0 dB in noise condition Lists presented in four conditions (noise/noise, noise/clear, clear/noise, and clear/clear for group 1/group 2), in which subjects either recalled group 1 or group 2 (though they were instructed to listen to and remember both groups) Seven trials per condition per subject Conditions appropriately counterbalanced	Method of cued serial recall Independent variables: noise (presence or absence), group of digits to be recalled (first or second half) Dependent variable: percentage of digits correctly recalled Subject's task: recall cued list in order after both groups of digits completely presented 89 subjects aged 25-69 yrs (mean of 45.3 yrs)
Study 3 (Ref. 1)	
Two prose passages, 682 and 712 words, from *Scientific American,* recorded at 120 words/min; presented through loudspeakers Passages re-recorded through a simulated telephone link incorporating an MNRU, adding no noise to entire passage, or adding no noise to first half of passage, but adding noise to second half of passage to maintain intensity 5 dB below intensity of signal Subjects answered ten simple questions to test recall: five could be answered only by reference to first half of passage, five by reference to second half	Method of cued recall Independent variables: noise (presence or absence and location) Dependent variable: percentage of questions answered correctly Subject's task: answer questions requiring specific recall of passage details 72 subjects for passage A; 52 subjects for passage B; total of 38 men and 86 women, aged 22-68 yrs (mean of 42.6 yrs)

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Experimental Results

- Signal-to-noise ratio that is sufficient to permit accurate identification (transcription) does not permit accurate recall of the same items ($p<0.001$). (Study 1; see Table 2).
- Presentation of earlier items in noise does not impair recall of later items presented without noise. (Study 2; see Table 3).
- Presentation of later items in noise does interfere with recall of earlier items presented without noise, whether random digits or coherent prose ($p<0.001$). (Study 3; see Table 4).

Variability

- Standard deviations for the different conditions are given in Tables 2-4. Significance of differences was determined by analysis of variance and Mann-Whitney *U* tests.

Table 2. Mean number of digit lists correctly repeated (transcribed) or recalled in the presence or absence of noise (Study 1). (Adapted from Ref. 1)

	Clear	Noise
Transcription	10.00 (0)	9.64 (0.48)
Memory	4.02 (3.9)	2.84 (4.2)

Standard deviations are given in parentheses.

Digit lists were presented without noise (clear) or with noise at a 0 dB signal-to-noise ratio.

Key References

*1. Rabbitt, P. M. A. (1968). Channel-capacity, intelligibility and immediate memory. *Quarterly Journal of Experimental Psychology*, 20, 241-248.

Cross References

4.101 Factors affecting acoustic memory;

8.304 Factors affecting the intelligibility of speech in noise;

8.305 Noise masking of speech: effect of signal-to-noise ratio

Table 3. Mean number of digit half-lists correctly recalled in the presence or absence of noise (Study 2). (Adapted from Ref. 1)

	Condition			
	Clear/clear	Clear/noise	Noise/noise	Noise/clear
Recall of first half	4.53 (3.46)	4.14 (3.8)	3.54 (3.01)	4.44 (2.97)
Recall of second half	6.10 (1.66)	5.67 (2.76)	5.91 (2.18)	6.31 (0.13)

Standard deviations are given in parentheses.

Each digit list was divided in half, with both halves presented without noise (clear), both halves presented with noise at a signal-to-noise ratio of 0 dB, or half the list presented with noise and half without, as indicated.

Table 4. Mean number of questions answered correctly for prose passages presented in the presence or absence of noise (Study 3). (Adapted from Ref. 1)

	First Half of Passage	Second Half of Passage
Passage A		
No noise	2.1 (1.7)	3.2 (1.9)
Clear/noise	1.7 (1.4)	2.5 (1.6)
Passage B		
No noise	1.8 (1.6)	2.6 (1.5)
Clear/noise	1.2 (1.1)	2.4 (1.8)

Standard deviations are given in parentheses.

Scores represent the mean number correct for questions relating to the first half or the second half of the passages (out of a total of five). Either the entire passage was presented without noise (clear) or the first half was presented without noise and the second half was accompanied by noise with a signal-to-noise ratio of 5 dB.

8.312 Methods of Reducing the Masking of Speech

Key Terms

Binaural unmasking; communications; earplugs; interaural phase difference; noise exclusion; noise masking; peak clipping; redundancy; vocal force

General Description

When speech is heard in the presence of noise, the intelligibility of the speech is frequently reduced. The degree to which the noise masks the speech depends primarily on the relative levels of the speech and the noise, and the degree to which the frequency components of the speech and noise overlap, although many other factors, including the content of the speech, affect intelligibility. The masking effect of noise on speech can be reduced by adopting communication practices that increase intelligibility, using procedures to minimize or exclude noise during speech pickup and transmission, and taking measures to reduce noise at the ear. These methods are described here in detail and are summarized in Table 1. Many other factors (such as the type of noise masking, the location of the sound sources, and the presence of visual cues) influence the perception of speech in noise (CRef. 8.304); attention to these factors can aid in improving speech intelligibility.

Communication Practices to Increase Intelligibility

The intelligibility of speech in noise is closely tied to the probability of occurrence of constituent speech sounds, words, or phrases. The greater the predictability (or the lower the uncertainty) of words, the higher the intelligibility of speech. This factor can be used advantageously in several ways to enhance intelligibility. For example, the vocabulary used to transmit messages can be standardized or the number of possible messages restricted (CRef. 8.309). In some communication contexts, constraints are imposed naturally by the specific situational context of the message. For example, the language of communications between pilots and air traffic controllers has its own peculiar grammar, known as RT procedures, which sets close constraints on message format and content. Additional constraints are imposed by the situation itself. Pilots familiar with RT procedures were asked to make predictions regarding the content of messages they might receive from an air traffic controller under specific conditions. Knowledge of the situational context was found to reduce the gross uncertainty of the message about 86% relative to unconstrained discourse. Linguistic constraints (based on RT procedures) reduce the residual uncertainty, in terms of letter sequences, another 72%, yielding an estimated redundancy of approximately 96% (Ref. 1). Thus it appears that standardization of the communication procedures called forth by the situational context can have a potent impact on the intelligibility of message sequences transmitted under suboptimal listening conditions.

The intelligibility of speech can also be improved through repetition, although the effects are not great. Repeating a word four times presented in noise increases its intelligibility by less than 7%, on average. Most of the benefit occurs by the second presentation (Ref. 8).

Table 1. Methods for reducing the masking of speech by noise.

1. Increase the redundancy of the speech (as by reducing the set of possible messages, adopting a standardized message grammar, employing words with higher frequency of usage, repeating the message, etc.)
2. Increase the level of the speech relative to the level of the noise
3. Utter the speech with moderate (versus high or low) vocal force
4. Peak-clip the speech signal and reamplify to original levels
5. Exclude noise at the microphone by using a throat microphone, pressure-gradient microphone, or noise shield
6. Provide intra-aural cueing by presenting the speech out of phase in the two ears
7. Use earplugs when noise levels are high

Noise Minimization During Speech Transmission

Signal Level. Increasing the level of the speech signal relative to that of noise can be an effective way to reduce masking effects. However, as Ref. 3 has pointed out, this may not be feasible for a variety of reasons:

1. With direct person-to-person communication, the intensity of the noise may be so great, or the listener so distant, that the speaker cannot override it.
2. When a communication system such as a radio or telephone is used, the system may lack the amplification power needed to override the effects of noise.
3. The masking noise may be mixed with speech at the microphone or in transmission such that increasing the amplitude of the message also increases the amplitude of the noise, leaving the signal-to-noise (S/N) ratio essentially constant.
4. The masking noise at the listener's ear may be so intense that increasing signal amplitude may overload the ear, causing signal distortion and/or pain.

An additional problem, present with both face-to-face and remote speech communication, is the effect of vocal force (vocal effort, from whisper to shout) on intelligibility. The problem is twofold in that high levels of vocal force introduce distortions both through overloading the speaker's vocal apparatus and through overloading the listener's ear. Speech uttered at very weak or very high levels of vocal effort is not as intelligible as speech uttered with moderate levels of vocal effort (CRef. 8.310).

Peak-Clipping. Certain portions of a speech waveform, usually those associated with consonants, are substantially less in amplitude than those associated with other parts (vowels). As a consequence, noise more effectively masks consonants than vowels. Peak-clipping can serve to increase the intensity level of consonants relative to vowels and thus to protect the more fragile components of speech units from the effects of noise. This is accomplished by passing the speech sound through a peak-clipper and then reamplifying the resulting signal to available peak power level (CRef. 8.313). Speech sounds processed in this fashion are

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more intelligible in noise than is unclipped speech. However, two potential problems exist with the procedure. First, speech which is peak-clipped by more than 6 dB and heard in quiet sounds relatively distorted and noisy. The problem is minimal under noisy listening conditions, though, because the noise tends to mask the speech distortion products resulting from clipping. Second, while peak clipping is beneficial when the speech signal is clipped before the introduction of noise, peak clipping may actually be detrimental to intelligibility under certain listening conditions when the speaker's voice is mixed with noise before clipping.

Noise Exclusion at the Microphone

It is desirable to minimize the intrusive effects of noise at the point of transmission. Several existing devices have been shown to be effective in excluding noise at the microphone. One such device is a microphone attached directly to the throat (throat microphone), where it picks up speech sounds conducted through body tissues, thereby excluding airborne noise. The throat microphone is quite effective at excluding airborne noise but tends to introduce troublesome distortions into the speech signal itself. Another effective device is the noise shield, which can be used to enclose an air-actuated microphone. Significant noise exclusion can be obtained with noise shields across the frequencies critical for speech intelligibility, that is, frequencies above about 500 Hz.

A third device that has proven effective in noise exclusion at the communication source is a close-talking pressure-gradient microphone. Here both surfaces of the active element in the microphone are exposed to the air. Sound waves associated with ambient noise will more or less impinge on both sides of the element simultaneously (depending on frequency) and thus tend to interfere with and cancel each other. Because of the small temporal delay between inputs to the two surfaces of the element, the effectiveness of cancellation will be maximal at low frequencies. When the microphone is held close to the lips, the speech signal will be highly directional, with an intensity differential at the two sides of the element sufficient to drive the microphone with minimum cancellation.

The pressure-gradient microphone is better than the microphone noise shield at excluding noise in the frequency range of ~300-700 Hz, which constitutes the dominant frequency range in speech.

Noise Minimization at the Ear

Substantial reductions in the masking effects of ambient noise present at the point of speech reception can be accomplished by intra-aural cueing and by the use of ear protectors.

Intra-aural Cueing. The intelligibility of speech has been studied under a variety of combinations of monaural and binaural listening to speech and noise over earphones (Ref. 5). The key findings are: (1) Under binaural speech and noise presentation, intelligibility is greatest when the phase relations of speech and noise at the two ears are opposite (i.e., when speech is in phase and noise 1803 out of phase, or the opposite); (2) intelligibility is much higher when noise is monaural and speech is binaural relative to when both are presented monaurally; and (3) when both speech and noise are given monaurally, intelligibility is substantially greater when the two are presented to opposite ears, as opposed to the same ear. Thus any procedure enabling the listener to lateralize speech and noise signals separately will aid intelligibility (CRef. 8.314).

Ear Protectors. Ear protectors, either earplugs or muffs, are commonly used to defend the ear from auditory fatigue induced by exposure to high-intensity noise. These devices attenuate speech and noise equally at any given frequency. Therefore they have no effect on frequency-specific S/N ratios. However, under conditions of intense noise (i.e., 90 dB or more), ear protectors usually contribute to speech intelligibility, because they reduce speech and noise sounds to levels where the ear is no longer overloaded (CRef. 8.316). Earplugs have a detrimental effect on intelligibility under conditions in which low levels of noise are present. Thus, earplug use poses a significant problem for communication within operational environments containing protracted periods of relative quiet and intermittent impulsive noise such as gunfire. Frequency-selective earplugs offer one approach to this problem. The acoustic trauma produced by high-intensity noise is associated with high-frequency components of the noise, those in the range of 3500-5000 Hz. Conversely, much of the acoustic information in normal speech communications is carried by frequencies below 4000 Hz. Earplugs that function as low pass filters are available and significantly increase speech intelligibility for the wearers while offering adequate protection of hearing under conditions of high-intensity impulsive noise (CRef. 8.316).

—Adapted from Ref. 2

Key References

1. Frick, F. C., & Sumby, W. H. (1952). Control tower language. *Journal of the Acoustical Society of America, 24*, 595-596.

2. Hawkins, H. L. & Presson, J. C. (1986). Auditory information processing. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance*. New York: Wiley.

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5. Licklider, J. C. R. (1948). The influence of interaural phase relations upon the masking of speech by white noise. *Journal of the Acoustical Society of America, 20*, 150-159.

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7. Pollack, I. (1958). Speech intelligibility at high noise levels: Effect of short-term exposure. *Journal of the Acoustical Society of America, 30*, 282-285.

8. Thwing, E. J. (1956). Effect of repetition on articulation scores for PB words. *Journal of the Acoustical Society of America, 28*, 302-303.

9. Zwislocki, J. J. (1951). Acoustic filters as ear defenders. *Journal of the Acoustical Society of America, 23*, 36-40.

Cross References

8.304 Factors affecting the intelligibility of speech in noise;

8.309 Noise masking of speech: effect of message set size;

8.310 Noise masking of speech: effect of vocal force;

8.313 Noise masking of speech: effect of peak clipping;

8.314 Noise masking of speech: effect of interaural phase relations;

8.316 Effect of earplugs on speech intelligibility as a function of received speech level

8.313 Noise Masking of Speech: Effect of Peak Clipping

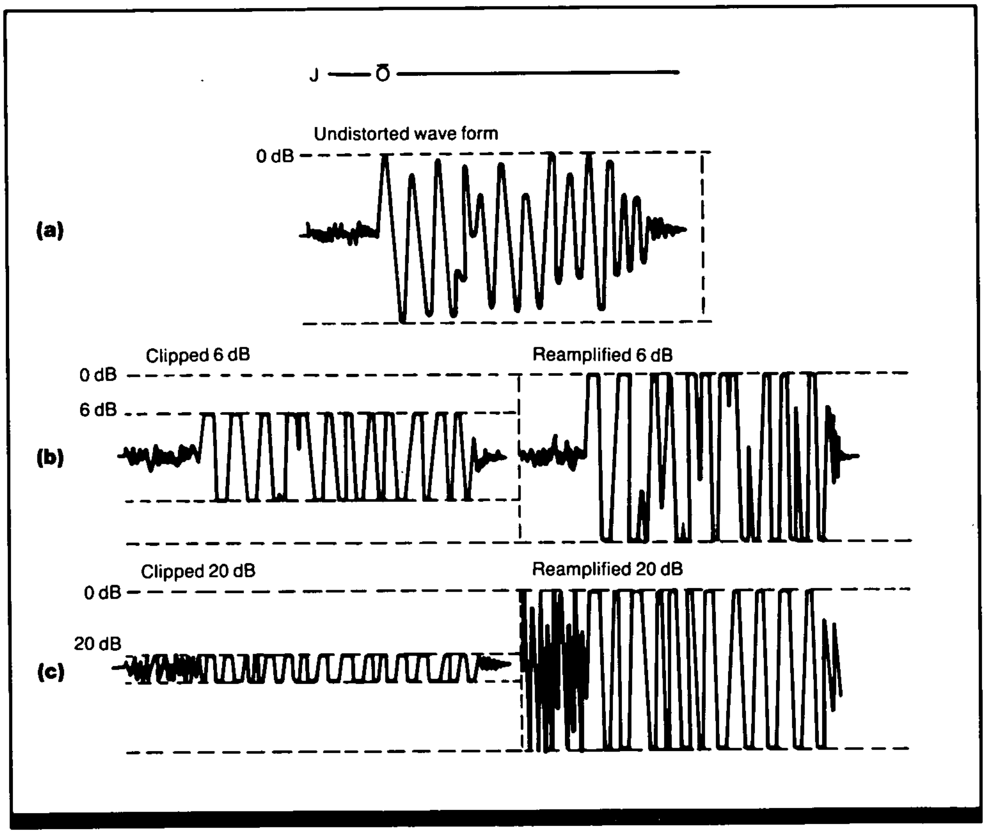

Figure 1. Illustration of peak clipping. Schematic representations of the speech waveform for the word *Joe*. Horizontal axis represents time; vertical axis, amplitude in decibels. (a) Undistorted waveform; (b) waveform after 6-dB peak clipping; (c) waveform after 20-dB peak clipping. Clipped signals in (b) and (c) are shown reamplified to the original signal level on the right. (From Ref. 3)

Key Terms

Amplitude distortion; communications; noise masking; peak clipping

General Description

Some portions of the speech waveform, generally those associated with consonant sounds, are substantially lower in amplitude than other parts associated with vowel sounds. Because of this, noise masks the consonant sounds of speech more effectively than it masks the vowel sounds. To protect these more fragile speech components from masking, the amplitude peaks of the speech waveform can be clipped, with the remaining signal reamplified to normal levels. This increases the intensity level of the consonants relative to the vowels and reduces the masking effects of noise. The procedure of peak clipping is shown in Figure 1. Peak clipping can be symmetric (both sides of the time axis are clipped) or asymmetric (only one side is clipped). Even with 90% of the speech wave clipped off, intelligibility remains high (90% correct identification of isolated words) when the clipped signal is reamplified to the original level. Intelligibility is lower when the speech is mixed with the noise before clipping than when there is no clipping or clipping is done prior to mixing the speech with noise. The quality of speech with various degrees of peak clipping is given in Table 1.

Methods

Test Conditions

- Discrete words spoken by two talkers were subjected to 0-100 dB peak clipping (20 dB implies reduction to 1/10 original amplitude) with reamplification to original level or subjected to infinite peak clipping (in which the speech wave is subjected to successive clipping and reamplification until a series of nearly rectangular waves is produced and then passed through a "flip-flop" circuit to eliminate any deviations from rectangularity)
- Speech signal 85 dB SPL
- Signal presented in quiet or in white noise with a level of 68, 73, 78, or 83 dB SPL

Experimental Procedure

- Independent variables: amount of peak clipping, noise level
- Dependent variable: percentage of words correctly identified
- Subject's task: identify word heard
- 2 subjects
- Each point represents mean of 30 presentations of 50 words

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Experimental Results

- Up to 20 dB peak clipping has no effect on the intelligibility of words in quiet.
- With peak clipping of >40 dB, intelligibility in quiet drops to 75% of normal.
- At low signal-to-noise ratios (<0 dB) infinite-clipped signals are more intelligible than non-clipped signals; at high signal-to-noise ratios (>10 dB), non-clipped signals are more intelligible.
- Adding noise before clipping reduces the beneficial effects of clipping.

Variability

Analysis of variance showed significance for all effects ($p<0.01$).

Constraints

- Practice improves intelligibility of severely clipped speech.
- Many factors (such as relative frequency of speech and noise, type of noise mask, speech message content, and listener's age) influence the intelligibility of speech in noise and must be considered in applying these results under different conditions (CRef. 8.304).

Key References

*1. Kryter, K. D. (1972). Speech communication. In H. P. Van Cott & R. G. Kinkade (Eds.), *Human engineering guide to equipment design* (pp. 161-226). Washington, DC: US Government Printing Office.

2. Licklider, J. C. R. (1946). Effects of amplitude distortion upon the intelligibility of speech. *Journal of the Acoustical Society of America, 18,* 429-434.

*3. Licklider, J. C. R., Bindra, D., & Pollack, I. (1948). The intelligibility of rectangular speech waves. *American Journal of Psychology, 61,* 1-20.

Cross References

8.304 Factors affecting the intelligibility of speech in noise;

8.312 Methods of reducing the masking of speech

Table 1. Quality of clipped and unclipped speech. (From Ref. 1)

Clipping (dB)	Sound in Quiet	Quality
0	Normal	Excellent
6	Essentially normal, effect barely detectable	Probably acceptable as of broadcast quality
12	As though talker enunciated with special care	Usable for military communication
18	Sharp, "sandy"	Fair, usable for most military communication
24	Coarse, "grainy"	Poor, but usable if intelligibility is of paramount importance

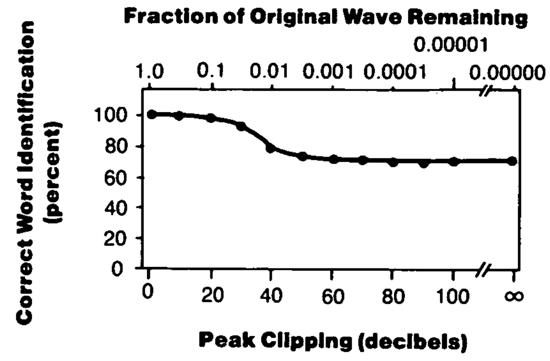

Figure 2. The effect of peak clipping on the intelligibility of single words in quiet. (From Ref. 3)

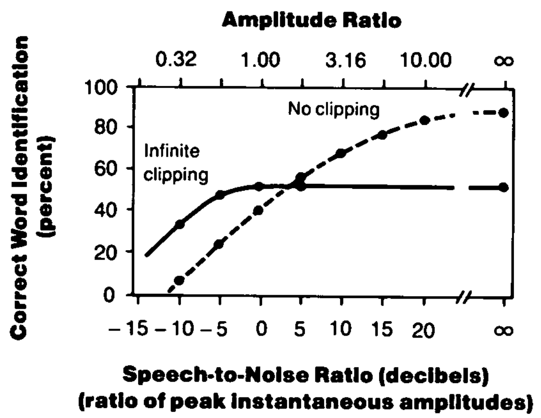

Figure 3. Intelligibility of single words heard in white noise with and without peak clipping of the speech signal, as a function of speech signal-to-noise ratio. Clipped and normal speech were equated in terms of peak amplitude. (An infinitely clipped speech signal is reduced to a series of nearly perfect rectangular waves.) (From Ref. 3)

8.314 Noise Masking of Speech: Effect of Interaural Phase Relations

Key Terms

Binaural unmasking; communications; interaural phase difference; noise making

General Description

The intelligibility of speech presented in white noise can be improved by altering the interaural phase relations of the speech or the noise (which changes the apparent spatial location of the sound source). Intelligibility is greatest when the noise is the same in both ears, but the speech is inverted (180 deg out of phase) in one ear relative to the other. Words are understood almost as clearly when the noise, rather than the speech, is out of phase in the two ears. Both of these manipulations can increase the intelligibility of words by as much as 25% over the normal condition with both speech and the noise in phase.

Applications

When ambient noise interferes with the intelligibility of speech presented through earphones, a small but significant improvement can be made by reversing the connections of one of the earphones to invert the speech signal in one ear.

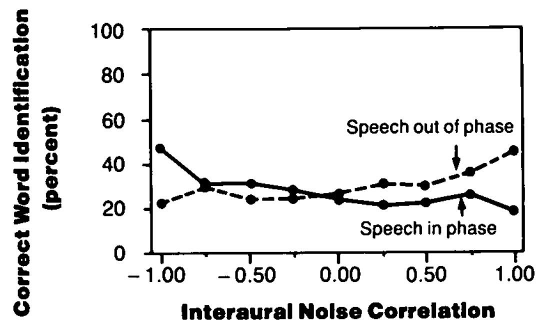

Figure 1. Intelligibility of speech in noise as a function of the phase relations of the speech and noise at the two ears. Percentage of words correctly identified is shown for different interaural noise correlations (where +1.00 indicates noise in phase and −1.00 noise 180 deg out of phase at the two ears). (From Ref. 1)

Methods

Test Conditions

- 18 lists of 50 phonetically balanced words, read by male talker and presented through headset
- Speech presented binaurally, in phase or out of phase in the two ears
- **White noise** mask presented binaurally, in phase, 180 deg out of phase, in random phase, or with interaural correlation of +1.00 to −1.00; noise level of 80 or 90 dB sound pressure level (SPL)
- Speech-to-noise ratio of 0 or −10 dB

Experimental Procedure

- Word identification
- Independent variables: interaural phase of signal, interaural phase of noise, speech-to-noise ratio, noise level
- Dependent variable: percentage of words correctly identified
- Subject's task: record each word heard
- 4 subjects

Experimental Results

- The intelligibility of speech in noise is highest (masking is least) when the noise is in phase in the two ears and the speech is out of phase; intelligibility is next highest when the speech is in phase and the noise is out of phase; intelligibility is lowest when both speech and noise are out of phase in the two ears (Table 1).
- Interaural phase effects are more pronounced at lower than at higher signal-to-noise ratios (Table 1).
- As the correlation between the noise in the left and right ears changes from +1.00 (in phase) to −1.00 (180 deg out of phase), speech intelligibility declines slightly when the speech signal is in phase in the two ears and increases slightly when the speech is out of phase. Most of the variation in intelligibility with interaural noise correlation is found for correlations of −0.75 to −1.00 and +0.75 to +1.00 (Fig. 1).
- A related experiment shows that speech intelligibility is almost 100% when signal and noise are presented to different ears.
- Altering the interaural phase relations of speech or noise alters its apparent spatial location. The more widely separated the speech and noise in phenomenal space, the less masking of speech by noise. The exception is when the noise is uncorrelated in the two ears: in-phase speech appears more spatially separate from the noise than out-of-phase speech, but the two are equally intelligible.

Variability

Standard errors range from 2.0-2.5.

Constraints

- The amount by which masking may be reduced by altering interaural phase depends upon the frequency of the signal, the noise bandwidth, interaural phase angle of the signal and the noise, and the age of the listener (CRefs. 2.314, 2.315, 8.315).
- Many factors affect the intelligibility of speech in noise and should be considered in applying these results under different conditions (CRef. 8.304).

Key References

*1. Licklider, J. C. R. (1948). The influence of interaural phase relations upon the masking of speech by white noise. *Journal of the Acoustical Society of America, 20,* 150-159.

Cross References

2.314 Binaural reduction of masking: effect of signal frequency and listening conditions;

2.315 Binaural reduction of masking: effect of interaural phase differences;

8.304 Factors affecting the intelligibility of speech in noise;

8.312 Methods of reducing the masking of speech;

8.315 Noise masking of speech: effect of interaural phase relations for listeners of different ages;

Handbook of perception and human performance, Ch. 14, Sect. 3.2; Ch. 26, Sects. 2.1, 5.4

Table 1. Intelligibility of speech in noise as a function of interaural phase relations for various noise levels and speech-to-noise ratios. (From Ref. 1)

		Interaural Phase Relations*					
Speech-to-Noise Ratio	Noise Level (in dB SPL)	1 (+ +)	2 (+ −)	3 (+0)	4 (− +)	5 (− −)	6 (−0)
		Percent Word Articulation					
0 db	90 db	69.4	77.4	73.6	79.4	68.4	72.3
−10 db	90 db	14.4	40.3	29.7	43.7	11.3	27.9
−10 db	80 db	18.0	35.4	27.4	43.0	15.8	27.3

*The first symbol refers to the speech waves, the second symbol refers to the noise waves: + in phase, − out of phase, 0 random phase.

8.315 Noise Masking of Speech: Effect of Interaural Phase Relations for Listeners of Different Ages

Key Terms

Age; auditory localization; binaural unmasking; communications; noise masking

General Description

When target words and background speech noise are presented together, the target words may be made more intelligible by presenting the noise at different perceived spatial locations relative to the source of the target words. This arrangement increases intelligibility to a greater extent for younger listeners (ages 23-32) than for older listeners (ages 60-72).

Methods

Test Conditions

- Speech stimuli were six lists of 25 one-syllable words selected from five pitch-related phonemic categories (150-400, 300-1200, 800-2400, 1200-3000, and 3200-12000 Hz) recorded monophonically by a male speaker; each word preceded by a warning signal and the phrase "The word is" 10 dB above the word amplitude
- Background noise was prose passages read by two males and two females recorded monophonically
- To create test stimuli, monophonic recordings of target word lists presented over speaker at 0 deg azimuth relative to artificial head and recorded stereophonically via microphones mounted on each side of artificial head; to create background noise, similar stereophonic recording made of monophonic recordings of four background voices presented simultaneously over four speakers located at ± 15 deg and ± 30 deg relative to artificial head
- Recordings played to subjects over TDH-49 headset in sound attenuated room
- Three listening conditions: target words only presented diotically (for baseline speech intelligibility threshold); target words and background voices mixed and presented **dichotically** (directional cues preserved); target words and background voices mixed and either left stereo channel or right stereo channel only presented diotically (directional cues removed)
- Background voices presented at fixed amplitude judged by experimenters to be "comfortable conversational level"; target list presented at 5 speech-to-noise ratios; initial level approximately 50 dB above baseline speech intelligibility threshold combined across both age groups; after every fifth word of target list, list amplitude level decreased by 5 dB
- Lists and order of presentation counterbalanced across subjects

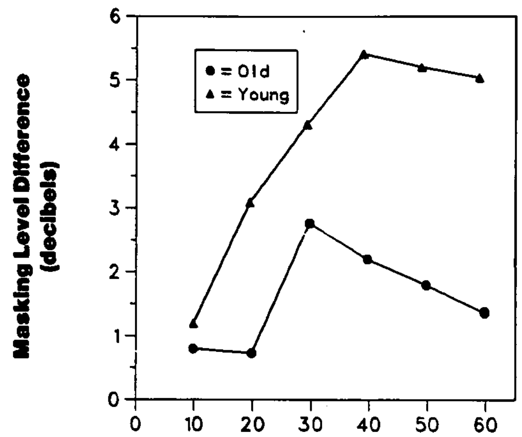

Figure 1. Masking level difference for speech in noise as a function of percentage of words correctly identified for younger and older subjects. Masking level difference is the amount by which the level of the target words may be reduced under dichotic relative to diotic presentation to maintain a given performance level. (From Ref. 1)

Experimental Procedure

- Method of constant stimuli
- Independent variables: pitch of target word, presence or absence of background voices, speech-to-noise ratio, age of subject
- Dependent variable: accuracy of identification of target words
- Subject's task: identify each target word as it is spoken
- Subjects: 8 males ages 22-32 (mean 26.5) and 8 males ages 60-72 (mean 66.0) with normal pure tone sensitivities and <10-dB ear difference below 2000 Hz, with some previous experience; older group had usual high-frequency hearing loss associated with aging and relatively larger ear differences

Experimental Results

- Target words presented in background speech noise are identified more accurately by the younger age group than by the older group at all speech-to-noise levels ($p < 0.0001$). The difference between groups is greatest at intermediate target speech levels.
- For both age groups, target words in noise are identified more accurately when the target words and the background speech noise appear to be coming from different spatial locations (dichotic listening conditions) than when target and noise appear to be coming from the same location (diotic listening).
- Young people benefit more from dichotic listening than do older people ($p < 0.0001$). The increase in speech intelligibility with dichotic versus diotic listening (the masking-level difference) is greater for the younger age group than the older age group at all performance levels; the difference is especially marked at speech levels where word identification accuracy is 30% or higher (Fig. 1).
- Pitch of words has no effect on intelligibility.

Variability

Significance of differences was determined by multivariate analysis for repeated measures.

Constraints

- Speech signals were individual words presented with a redundant and non-informative context; results may be different when speech signals are coherent conversation.
- Because only two age groups are tested, it is not clear whether there is a progressive trend with age.
- The amount by which noise masking may be reduced by presenting signal and noise to different spatial locations depends upon the frequency of the signal, the noise bandwidth, and apparent spatial location (interaural phase angle) of the signal and the noise (CRefs. 2.314, 2.315).
- Many factors affect the intelligibility of speech in noise and should be considered in applying these results under different conditions (CRef. 8.304).

Key References

*1. Warren, L. R., Wagener, J. W., & Herman, G. E. (1978). Binaural analysis in the aging auditory system. *Journal of Gerontology, 33*, 731-736.

Cross References

2.314 Binaural reduction of masking: effect of signal frequency and listening conditions;

2.315 Binaural reduction of masking: effect of interaural phase differences;

7.209 Factors influencing performance in selective listening tasks;

7.212 Selective listening: effect of age;

8.304 Factors affecting the intelligibility of speech in noise;

Handbook of perception and human performance, Ch. 26, Sects. 3.2, 6.1

8.316 Effect of Earplugs on Speech Intelligibility as a Function of Received Speech Level

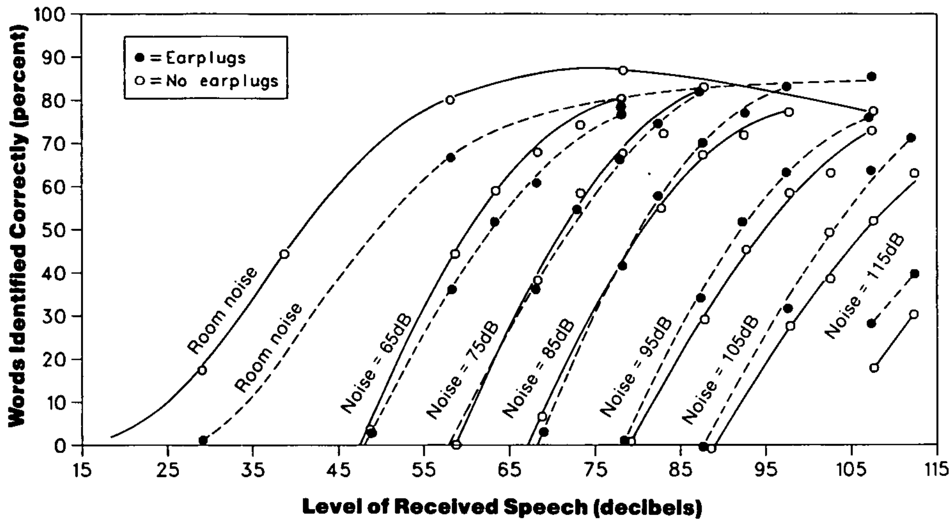

Figure 1. Effect of earplug use on the intelligibility of one-syllable words presented in noise. Speech was presented over a public address system in a reverberant room at the level indicated (Study 1). (From Ref. 1)

Key Terms

Communications; earplugs; noise exclusion; noise masking; signal-to-noise ratio; speech level

General Description

Under noise conditions that raise the signal threshold at least 60 dB, earplugs increase the intelligibility of speech delivered via a public address system. Under quieter conditions, earplugs decrease speech intelligibility. In a reverberant room under face-to-face speaking conditions with a low signal-to-noise ratio, earplugs do not have a deleterious effect on speech intelligibility, but do not improve it either. In face-to-face speaking conditions, wearing earplugs causes speakers to drop their voice levels 1-2 dB. Earplugs specially designed to pass a part of the speech frequencies more than double speech intelligibility compared with earplugs that attenuate the whole audible frequency range.

Methods

Test Conditions

Study 1 (Ref. 1)

- Lists of monosyllabic phonetically balanced words (i.e., lists in which the frequency of occurrence of various phonemes is proportional to their occurrence in everyday English) read over public address system to subjects 3.7 m (12 ft) from loudspeaker or read directly (face-to-face) to subjects seated 2.1 m away
- Test conducted (1) in reverberant chamber, with frequency spectrum approximating acoustical conditions of engine room of submarine or warship, in the quiet or with noise at signal-to-noise ratios of −5, 0, 5, 10, or 15 dB; or (2) in a non-reverberant (anechoic) chamber in the quiet
- Subjects (listeners) wore or did not wear earplugs; in face-to-face conditions, speakers wore or did not wear earplugs

Study 2 (Ref. 2)

- Words presented to subjects in a quiet environment
- Subjects (1) wore normal earplugs that attenuated entire audible frequency range, (2) wore earplugs with channels of two different diameters to permit passage of different frequency bands, which acted as low-pass filters; or (3) did not wear earplugs

Experimental Procedure

- Independent variables: signal-to-noise ratio, type of acoustic environment, type of presentation, presence versus absence of earplugs (Study 1); presence or absence of earplugs, type of earplug (Study 2)
- Dependent variables: speaker intensity level, percent correct word identification (Study 1); percent correct word identification (Study 2)
- Subject's task: report word heard on each presentation
- 8 college-age male subjects (Study 1); 10 normal-hearing subjects (Study 2)

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- For speech presented over a public address system in a reverberant room, speech intelligibility is as high or higher when earplugs are worn as when they are not worn at noise levels >80 dB. The use of earplugs decreases intelligibility slightly for noise levels <80 dB (Fig. 1).
- Similar results are found when listening takes place in an anechoic chamber rather than reverberant room (data not shown).
- With face-to-face speaking in a reverberant room at high noise levels (100 dB), the wearing of earplugs does not decrease speech intelligibility.
- At noise levels of 75-105 dB, the use of earplugs by speakers causes speech intensity to drop 1-2 dB for face-to-face speaking. In the quiet, speakers wearing earplugs raise voice intensity by 3 dB in face-to-face speaking.
- In a quiet environment where speech intelligibility of 100% is possible at 48 m when the listener does not wear earplugs, the use of earplugs that attenuate the whole audible frequency range reduces the distance for 100% intelligibility to 14 m; with non-linear (low-pass) earplugs, nearly all words can be understood at 30-39 m.

Variability

No information on variability was given.

Constraints

- Many factors (such as relative frequency of speech and noise, type of noise mask, speech message content, and listener's age) influence the intelligibility of speech in noise and must be considered in applying these results under different conditions (CRef. 8.317).

Key References

*1. Kryter, K. D. (1946). Effects of ear protective devices on the intelligibility of speech in noise. *Journal of the Acoustical Society of America, 18*, 413-417.

*2. Zwislocki, J. (1951). Acoustic filters as ear defenders. *Journal of the Acoustical Society of America, 23*, 36-40.

Cross References

8.302 Effect of filtering on speech intelligibility;

8.304 Factors affecting the intelligibility of speech in noise;

8.312 Methods of reducing the masking of speech;

8.317 Methods of predicting speech intelligibility;

Handbook of perception and human performance, Ch. 26, Sect. 5.4

8.317 Methods of Predicting Speech Intelligibility

Key Terms

Articulation index; noise masking; noise criteria contour; perceived noise level; sound level meter; speech interference level; speech intelligibility; sound level

General Description

Virtually every environment in which people live and work contains some level of noise. When the level of the noise is high enough, the noise may interfere with the perception of speech. So that adequate steps may be taken to ensure intelligibility in settings where speech communication is necessary, various procedures have been developed to predict the speech-interfering effects of noise in a given environment or communications system from the relative levels of the speech and the noise, without having to resort to direct tests of speech perception. Several methods have been developed for making such estimates of speech intelligibility in noise.

The simplest approach to assessing the effects of noise is to measure the sound pressure level of the noise with a sound level meter. Sound level meters measure only loudness. They are equipped with three weighting networks (A, B, and C) which emphasize some frequencies and attenuate others in order to make the reading correspond more closely to the subjective effects of the sound. The weighting networks are standard filters whose frequency responses approximate the human equal-loudness contours for pure tones with loudness levels of 30-60 phons (A), 60-90 phons (b) and >90 phons (C). The sound pressure level of a noise measured with the meter set on the B or C scale does not necessarily bear any strong relation to the intelligibility of speech heard in that noise. Measurements made using the A weighting scale show considerably better correlation with intelligibility, but their predictive power is still weak. Several specialized methods have been developed for predicting the intelligibility of speech in noise.

The noise criteria (NC) method was developed as a means of assessing the effect of room noise on speech communication (Refs. 2, 3). In this method, the octave-band spectrum of the noise in a room is first plotted. This spectrum is then compared with published NC contours showing the permissible sound-pressure levels in eight octave bands for various levels of communication. The numerical value of the highest NC contour touched by any octave band of the noise is assigned to the noise spectrum being considered. NC contour indexes generally run from 20 (indicating a very quiet office environment in which telephone use is satisfactory and large conferences are possible) to 70 (indicating a very noisy environment with a raised-voice range of ~0.3-0.6 m [1-2 ft] and a shouting range of ~1-2 m [3-6 ft], in which telephone use is very difficult). The NC method works well in rooms where the noise is primarily of low frequencies (e.g., noise produced by motor vehicles, ventilation systems, etc.).

The PNdB (perceived noisiness) (Ref. 8) method is similar to the NC method. However, the equal-noisiness contours used for weighting the different frequency bands of noise to derive a PNdB value are similar in shape to the typical speech spectrum over the region of 500-3000 Hz. Thus, the contours weight the frequency bands of the noise in inverse proportion to the amount of speech energy present in the 500-3000 frequency range. In addition, the PNdB takes account of relatively sharp peaks and valleys in the octave-band and one-third-octave-band spectra of the noise, variations that influence the masking effectiveness of the noise. The PNdB method is frequently used to estimate the general subjective noisiness or acceptability of aircraft noise.

The articulation index (AI) is a more complex but more precise method of determining the intelligibility of speech communication in a given acoustical environment (Refs. 4, 6). The difference between the level of the speech and the level of the noise is measured in 20 contiguous frequency bands that contribute equally to speech intelligibility when all frequencies are at optimal gain. The average difference between signal and noise across all bands is normalized to yield a value between 0 and 1.0, which is the articulation index. A value of 0 indicates that the listener will rarely be able to understand any speech, while a value of 1.0 indicates essentially perfect perception by the listener. The articulation index may also be calculated using octave bands or one-third octave bands rather than the 20 equalized frequency bands, but the measure will not be as precise. The articulation index may be used to predict speech intelligibility in any noise setting, but it is complex and time-consuming to compute.

To predict the intelligibility of speech in face-to-face communication in noisy environments, the speech interference level (SIL) is often calculated (CRef. 8.318; Refs. 1, 9). The SIL method yields the maximum noise level that allows 75% correct perception of phonetically balanced test words and 98% correct perception of test sentences (equivalent to an AI of 0.5). The index is calculated by taking the arithmetic average of the sound pressure level of the noise in the octave bands 600-1200, 1200-2400, and 2400-4800 (sometimes slightly different octave bands are employed). The SIL is useful only in environments where the noise is relatively continuous (e.g., ventilation-system noise, engine-room noise, etc) and for broad-band noise whose spectrum contains no sharp peaks or valleys. The SIL is slightly less accurate than the articulation index in predicting speech intelligibility, but it is much faster and simpler to calculate.

Several studies have compared the effectiveness of the methods described above in predicting the intelligibility of speech in the presence of certain types of noise. In one study (Ref. 8), noises from several different types of jet and propeller-driven aircraft were recorded during takeoffs, landings, and ground runups. These recordings were mixed with test recordings of spoken words at several speech-to-noise ratios and trained listeners were tested for recognition of the spoken words. Under these conditions, the articulation index proved to be the best predictor of the speech-interference effects of the aircraft noise. Sound pressure level of the noise measured using the C scale of a sound level meter was the worst predictor. The PNdB, SIL, and NC methods and physical measurements using the A meter weighting scale were about equal in their ability to predict speech intelligibility with aircraft noise, although all were less useful than the AI.

In a similar study which tested the intelligibility of speech presented in 16 different shipboard noises (Refs. 5, 10), the AI, as well as SIL calculations that included the 300-600 Hz octave band, were found to be good predictors of speech-interference effects of the noise, with the AI marginally better. The next best predictors were physical measurement with the sound level meter A scale and SIL measurement using 600-4800 Hz bands. B and C frequency weighting networks and the conventional NC method yielded generally poor results for these types of noise.

Constraints

• How well a given index will predict intelligibility in a specific setting depends on the spectral characteristics and temporal parameters of the noise.

• Speech intelligibility in noise is influenced by many factors in addition to the relative levels of the speech and noise (CRef. 8.304).

Key References

1. Beranek, L. L. (1950). Noise control in office and factory spaces. Fifteenth annual meeting of the Chemical Engineers Conference. *Transactions Bulletin, 18,* 26-33.

2. Beranek, L. L. (1957). Revised criteria for noise in buildings. *Noise Control, 3* (1), 19-27.

3. Beranek, L. L. (1960). Criteria for noise and vibration in buildings and vehicles. In *Noise reduction* (p. 514). New York: McGraw-Hill.

4. French, N. R., & Steinberg, J. C. (1947). Factors governing the intelligibility of speech sounds. *Journal of the Acoustical Society of America, 19,* 90-119.

5. Klumpp, R. G., & Webster, J. C. (1963). Physical measurements of equally speech-interfering navy noises. *Journal of the Acoustical Society of America, 35,* 3128-1338.

6. Kryter, K. D. (1962). Methods for the calculation and use of the Articulation Index. *Journal of the Acoustical Society of America, 34,* 1689-1697.

7. Kryter, K. D. (1972). Speech communication. In H. P. Van Cott & R. G. Kinkade (Eds.), *Human engineering guide to equipment design* (pp. 161-226). Washington, DC: U.S. Government Printing Office.

8. Kryter, K. D., & Williams, C. E. (1965). Masking of speech by aircraft noise. *Journal of the Acoustical Society of America, 37,* 138-150.

9. Rosenblith, W. A., & Stevens, K. N. (1953). *Handbook of acoustic noise control. Vol. 2: Noise and man* (Tech. Rep. 52-204). Wright-Patterson Air Force Base, OH: Wright Air Development Center.

10. Webster, J. C., & Klumpp, R. G. (1963). Articulation index and average curve-fitting methods of predicting speech inteference. *Journal of the Acoustical Society of America, 35,* 1339-1344.

Cross References

2.104 Calibration procedures and instruments for measuring sound

8.304 Factors affecting the intelligibility of speech in noise

8.318 Speech interference level index

8.318 Speech Interference Level Index

Key Terms

Communications; listening distance; noise masking; speech interference level

General Description

The speech interference level (SIL) is a commonly used index for predicting the intelligibility of face-to-face speech communication in environments where there is relatively continuous noise (such as ventilation-system noise, aircraft noise, engine room noise, or factory machine noise). The SIL is faster and easier to calculate than the articulation index (AI), although it is a slightly less accurate predictor of intelligibility than the AI. The SIL method calculates the maximum noise level that allows 75% correct perception of phonetically balanced (PB) words and 98% correct perception of test sentences, about equal to an AI of 0.5. (Phonetically balanced words are lists of words equated for consonant and vowel sounds in which the frequency of occurrence of the various speech sounds is proportional to that of everyday speech; such word lists are frequently used in intelligibility testing.)

The SIL for a given noise is determined as follows:

a. Measure the sound pressure level of the noise in the octave bands of 600-1200, 1200-2400, and 2400-4800 Hz; sometimes the octave band 300-600 is also included. Or the bands 700-1400, 1400-2800, and 2800-5600 Hz may be used, and are considered preferable (Ref. 1).

b. Calculate the arithmetic average of the decibel levels of the noise in these octave bands; this average is the SIL. (Fig. 1 can be used to convert spectrum levels to octave-band spectra, and vice versa.)

c. Table 1 can be used to determine the maximum distance between speaker and listener at which 75% of the PB test words will be identified correctly when spoken with a given level of vocal force.

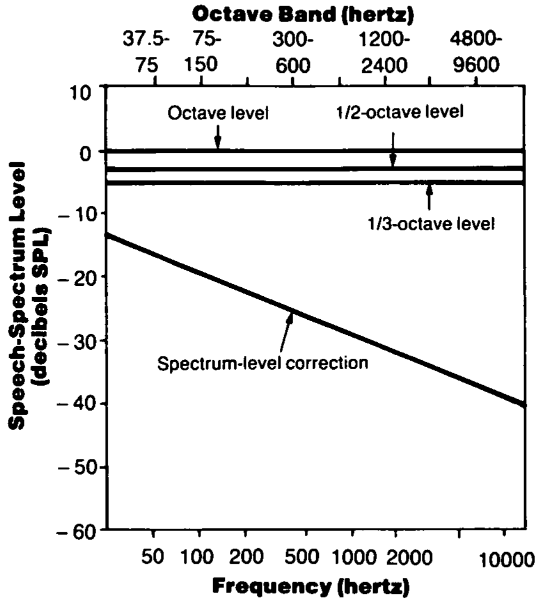

Figure 1. The relationship among octave, one-half octave, one-third octave, and spectrum level. (From Ref. 3)

Constraints

- The SIL should be used under conditions where there is relatively continuous noise.
- Many factors (such as the type of noise mask, speech message content, and listener's age) influence the intelligibility of speech in noise (CRef 8.304).

Key References

1. Beranek, L. L. (1949). *Acoustic measurements*. New York: Wiley.

2. Beranek, L. L. (1950). Noise control in office and factory spaces. *Fifteenth Annual Meeting of the Chemical Engineers Conference. Transactions Bulletin, 18*, 26-33.

*3. Kryter, K. D. (1972). Speech communication. In H. P. Van Cott & R. G. Kinkade (Eds.), *Human engineering guide to equipment design* (pp. 161-226). Washington, DC: U.S. Government Printing Office.

Cross References

8.304 Factors affecting the intelligibility of speech in noise;

8.317 Methods of predicting speech intelligibility

Table 1. Speech interference level permitting barely reliable speech communication. (From Ref. 1)

Distance Between Talker and Listener in Feet (meters)	Speech Interference Level (dB)*			
	Normal†	Raised†	Very Loud†	Shouting†
0.5 (0.152)	71	77	83	89
1.0 (0.305)	65	71	77	83
2.0 (0.61)	59	65	71	77
3.0 (0.915)	55	61	67	73
4.0 (1.22)	53	59	65	71
5.0 (1.525)	51	57	63	69
6.0 (1.83)	49	55	61	67
12.0 (3.66)	43	49	55	61

*Correct recognition of 75% of PB words

†Voice level

8.401 Effect of Age on Perception of Altered and Unaltered Speech

Key Terms

Age; altered speech; auditory masking; communications; dichotic listening; filtered speech; interrupted speech; overlapping speech; reverberation; speech distortion; speeded speech

General Description

The perception of degraded (distorted or interrupted) speech declines with age for listeners who show normal pure-tone thresholds. The decline begins to be noticeable in the fifth decade of life and accelerates sharply in the seventh decade. Perception of normal (unaltered) speech also declines slightly with age, but the decline is much less than for altered speech.

Methods

Test Conditions

- Battery of isolated words and everyday sentences from Ref. 2 spoken by five speakers of varying sexes, ages, and accents
- Stimuli presented undistorted (Curve 1 in Fig. 1); speeded up from 120 words/min to 300 words/min (Curve 2); binaurally filtered so that one ear heard a low-frequency band of 500-800 Hz, while the other heard a high-frequency band of 1800-2400 Hz (Curve 3); masked by simultaneous presentation of other voices (Curve 4); presented with acoustic reverberation (Curve 5); presented dichotically (single words only) so that second syllable of one word overlapped first syllable of next word (Curve 6); or electronically interrupted 8 times/sec (Curve 7)
- Listening conditions are not fully described, but the materials were presented at test sites with high ambient noise levels

Experimental Procedure

- Cross-sectional and longitudinal designs
- Independent variables: age of subject, stimulus-degradation condition
- Dependent variable: percentage of words or sentences heard correctly
- Subject's task: report words or sentences heard
- Subjects for one-time (cross-sectional) study: 282 healthy adults, 20-80 yrs, with audiometric hearing levels >35 dB at 500, 1000, and 2000 Hz and >40 dB at 4000 Hz; 1534 subjects per age group
- Subjects for lifetime (longitudinal) study: 54 subjects from original study, 40-89 yrs, tested 3 yrs later, 11 of whom were not native English speakers (and not included in later data analysis); 55 subjects from original study, 20-69 yrs, tested 7 yrs later, 19 of whom also participated in 3-yr follow-up
- All participating subjects passed an initial pure-tone screening test indicating that hearing was within normal limits

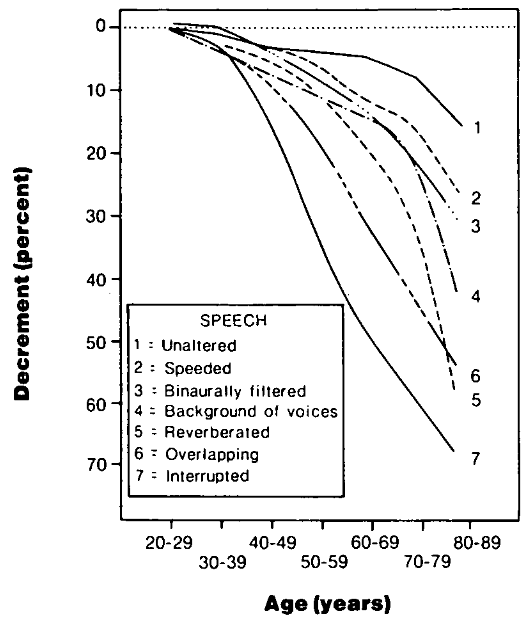

Figure 1. Speech intelligibility as a function of age for altered and unaltered speech. Performance of 20- to 29-yr-olds is taken as the 0 level and the decrement in performance relative to that level is calculated for the other age groups. (From Ref. 1)

Experimental Results

- Perception of speech under non-optimal conditions declines with age, starting by the fifth decade of life and sharply accelerating during the seventh decade (Fig. 1).
- Speech perceptibility declines with age, markedly so after 60 yrs, even with undistorted speech.
- Distorting or interfering with speech produces more profound decrements in perceptibility for older than for younger subjects.
- Interfering with speech is much more disruptive than distorting speech to listeners over 50 yrs old.
- Figure 1 shows results from cross-sectional study; results were confirmed in the longitudinal study.
- Non-native English speakers identify English speech more poorly than native English speakers, despite extensive experience (50 yrs) with the English language (data not shown).

Variability

No specific information on variability was reported.

Constraints

- Many details of the listening conditions and subject's task are not reported.
- Speech intelligibility is influenced by the type of test materials used and the presence of visual (lip-reading) cues (CRefs. 8.301, 8.303).

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Bergman, M., Blumenfeld, V. G., Cascardo, D., Dash, B., Levitt, H., & Margulies, M. K. (1976). Age-related decrement in hearing for speech. Sampling and longitudinal studies. *Journal of Gerontology, 31*, 533-538.

2. Davis, H., & Silverman, S. R. (1970). *Hearing and deafness*. New York: Holt, Rinehart & Winston.

Cross References

7.212 Selective listening: effect of age;

7.217 Divided attention: effect of age;

8.301 Effect of type of test material on speech intelligibility;

8.302 Effect of filtering on speech intelligibility;

8.303 Effects of visual cues on speech intelligibility;

8.304 Factors affecting the intelligibility of speech in noise;

8.315 Noise masking of speech: effect of interaural phase relations for listeners of different ages;

8.402 Regularly repeated interruption of speech;

Handbook of perception and human performance, Ch. 26, Sect 6.2.

8.402 Regularly Repeated Interruption of Speech

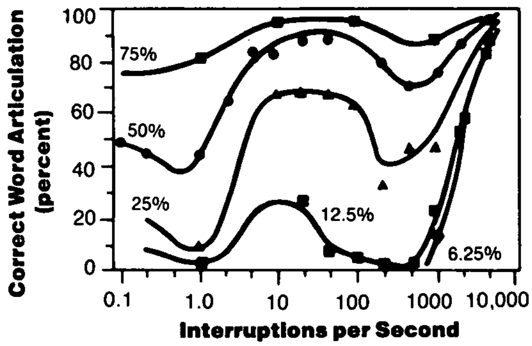

Figure 1. Intelligibility of speech interrupted by silent periods. The percentage of words identified correctly is shown as a function of the rate of interruption for five speech-time fractions (percentage of time the speech was left on). (From Ref. 1)

Key Terms

Communications; interrupted speech; speech intelligibility

General Description

Speech intelligibility is adversely affected by regularly repeated interruptions of the speech. Decreasing the speech-time fraction (percentage of time speech is audible, compared to interrupted) tends to decrease the intelligibility. The relationship between the frequency of interruption and speech intelligibility is more complex. For a given speech-time fraction, intelligibility is poorest at 1 interruption/sec. Intelligibility improves as the frequency of interruption increases above 1/sec, but the function shows another minimum in the range of 200-1000 interruptions/sec before improving again.

Methods

Test Conditions

- Target vocabulary was list of phonetically balanced monosyllabic words (lists in which the frequency of occurrence of various **phonemes** is proportional to their occurrence in everyday English) phonographically recorded by two people, and produced for articulation testing by equalized playback via earphones (Permoflux dynamic receivers PDR-8)
- Speech was interrupted by electronic switch which attenuated signal by 80 dB; interruption rates of 0.1-10,000/sec; speech-time fractions of 6.25%, 12.5%, 25%, 50%, and 75%

Experimental Procedure

- Independent variables: frequency of interruption, speech-time fraction
- Dependent variable: percentage of words reported correctly (word articulation)
- Subject's task: transcribe word presented
- 5 male subjects

Experimental Results

- The intelligibility of interrupted speech increases as the speech-time fraction increases.
- For all speech-time fractions tested (except for the shortest fraction, 0.0625) intelligibility is poorest at interruption rates of ~1 interruption per sec and ~200-1000 interruptions per sec.
- If the rate of interruption is high enough, almost all of the words can be understood, regardless of speech-time fraction.

Constraints

- These results are only for speech interrupted by quiet in a regular, predictable manner. Real world interruptions of speech are often noisy and temporally irregular.
- The intelligibility of interrupted speech declines as the age of the listener increases (CRef. 8.401).
- Speech intelligibility is influenced by many factors, including the presence of noise, visual (lip-reading) cues, and the type of test material used (CRefs. 8.301, 8.302, 8.303, 8.304).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Miller, G. A., & Licklider, J. C. R. (1950). The intelligibility of interrupted speech. *Journal of the Acoustical Society of America*, *22*, 167-173.

Cross References

8.301 Effect of type of test material on speech intelligibility;

8.302 Effect of filtering on speech intelligibility;

8.303 Effect of visual cues on speech intelligibility;

8.304 Factors affecting the intelligibility of speech in noise;

8.401 Effect of age on perception of altered and unaltered speech

8.403 Frequency-Shift Distortion of Speech

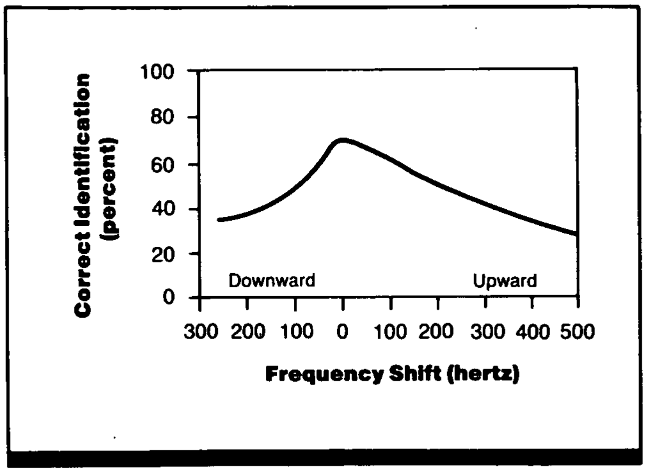

Figure 1. Intelligibility of nonsense syllables as a function of upward or downward shift in the frequency of the speech signal. (From Ref. 2)

Key Terms

Communications; frequency shift; speech distortion; speech intelligibility

General Description

Speech sent from one point to another by single side-band transmission will be distorted if the two channels are not precisely synchronized. A constant number of hertz is added or subtracted from each frequency component, i.e., the whole speech spectrum is shifted up or down the frequency scale. An upward shift of 100 Hz produces 10% loss of intelligibility; an equal shift downward produces a 20% loss.

Methods

Test Conditions

- Recorded nonsense syllables shifted in frequency up by 0-500 Hz or down by 250 Hz

Experimental Procedure

- Independent variable: amount and direction of frequency shift
- Dependent variable: percentage of nonsense syllables reported correctly
- Subject's task: write each syllable heard
- No subject information given

Experimental Results

- An upward frequency shift of 100 Hz produces a 10% loss of intelligibility for nonsense syllables.
- A 500-Hz upward frequency shift produces a nearly 50% loss of intelligibility.
- Downward frequency shifts produce somewhat greater loss of intelligibility than equal upward shifts.

Constraints

- Music is much more severely distorted than speech by frequency shift.
- The intelligibility of altered speech declines with the age of the listener (CRef. 8.401).
- Speech intelligibility is influenced by many factors, including the presence of noise, visual (lip-reading) cues, and the type of test material used (CRefs. 8.301, 8.302, 8.303).

Key References

*1. Fletcher, H. (1929). *Speech and hearing*. New York: Van Nostrand.

*2. Licklider, J. C. R., & Miller, G.A. (1951). The perception of speech. In S. S. Stevens (Ed.). *Handbook of experimental psychology*, (pp. 1040-1074). New York: Wiley.

Cross References

8.301 Effect of type of test material on speech intelligibility;

8.302 Effect of filtering on speech intelligibility;

8.303 Effects of visual cues on speech intelligibility;

8.304 Factors affecting the intelligibility of speech in noise;

8.313 Noise masking of speech: effect of peak clipping;

8.401 Effect of age on perception of altered and unaltered speech;

8.404 Compression or expansion of the time scale of speech

8.404 Compression or Expansion of the Time Scale of Speech

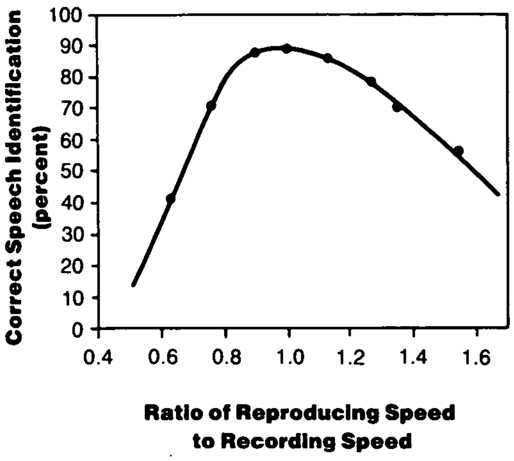

Figure 1. Intelligibility of speech with compressed or expanded time scale. Percentage of speech heard correctly is shown as a function of the ratio of playback speed to recording speed. (From Ref. 3)

Key Terms

Communications; retarded speech; speech intelligibility; speech rate; speeded speech

General Description

The time scale of a speech signal can be altered by recording speech at one rate and playing it back at another. This has the effect of altering the frequency components of speech: altering the time by a factor of *N* multiplies all frequency components by *N*. Playing the speech at 0.8-1.3 times its original speed has little effect on intelligibility, but reducing the rate to ~0.65 lowers intelligibility by almost half, and increasing it to ~1.5 times the original speed reduces intelligibility to 55%.

Applications

Somewhat faster transmission rates may be achieved with little loss in intelligibility by simply playing back speech at a faster rate than the speech at which it was recorded. Speech intelligibility is only slightly affected by small mismatches between recording and playback rates.

Methods

Test Conditions

- Recording of speech played back at 0.63, 0.77, 0.9, 1.0, 1.13, 1.27, 1.35, or 1.53 times recording speed
- No other details of test conditions known

Experimental Procedure

- Independent variable: playback speed relative to recording speed
- Dependent variable: speech identification accuracy (percentage articulation)
- Subject's task: write what was heard
- Number of subjects not reported
- No other details of procedure known

Experimental Results

- Altering the playback rate for speech by 25% or less of the recorded rate decreases intelligibility by only ~20%.
- Increasing playback rate to ~1.5 times the recorded rate yields articulation scores of 55%.
- Slowing the speech playback rate substantially reduces intelligibility more than speeding it substantially.

Variability

No information on variability is known.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- The intelligibility of altered speech declines with increasing age of the listener (CRef. 8.401).
- Speech intelligibility is influenced by many factors, including the presence of noise, visual (lip-reading) cues, and the type of test material used (CRefs. 8.301, 8.302, 8.303, 8.304).

Key References

1. Fletcher, H. (1929). *Speech and hearing*. New York: Van Nostrand.

*2. Fletcher, H. (1972). *Speech and hearing in communication*. Huntington, NY: Robert E. Krieger.

*3. Licklider, J. C. R., & Miller, G. A. (1951). The perception of speech. In S. S. Stevens (Ed.). *Handbook of experimental psychology* (pp. 1040-1074). New York: Wiley.

Cross References

8.301 Effect of type of test material on speech intelligibility;

8.302 Effect of filtering on speech intelligibility;

8.303 Effect of visual cues on speech intelligibility;

8.304 Factors affecting the intelligibility of speech in noise;

8.313 Noise masking of speech: effect of peak clipping;

8.401 Effect of age on perception of altered and unaltered speech;

8.403 Frequency-shift distortion of speech

Notes

Key Terms

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Glossary

Accommodation. A change in the thickness of the lens of the eye (which changes the eye's focal length) to bring the image of an object into proper focus on the retina. (CRef. 1.222)

Alveolar. Articulated with the tip of the tongue placed against part or all of the ridge behind the upper teeth (as in [t], [s], [n].)

Articulator. A moveable organ such as the tongue, lips, or uvula, that is used in the production of speech.

Decibel. The standard unit used to express the ratio of the power levels or pressure levels of two acoustic signals. For power, one decibel = 10 log P_1/P_2 (where P_1 and P_2 are the powers of the first and second signals, respectively). For pressure, one decibel = 20 log p_1/p_2 (where p_1 and p_2 are the sound pressure levels of the two signals). In most applications, the power or pressure of a signal is expressed relative to a reference value of $P_2 = 10^{-12}$ W/m² for power and $p_2 = 20$ μPa (or 0.0002 dynes/cm²) for pressure.

Dependent variable. The response to a stimulus presentation measured by the investigator to assess the effect of an experimental treatment or independent variable in an experiment; for example, the investigator might measure the auditory threshold (dependent variable) for several tones that differ in sound frequency (independent variable). (*Compare* **independent variable.**)

Dichotic. Pertaining to listening conditions in which the sound stimulus to the left and right ears is not identical but differs with respect to some property (such as frequency or phase).

Difference threshold. The least amount by which two stimuli must differ along some dimension to be judged as nonidentical. Usually taken as the difference value associated with some specified probability of detecting a difference (typically 0.50 or 0.75).

Diphthong. A gliding, monosyllabic vowel sound that undergoes a shift in vowel quality from start to finish, such as the vowel combination at the end of the word *boy.*

Formant. One of several bands of frequencies apparent in the spectrum of a vowel sound that are associated with resonance of the vocal tract and determine the phonetic quality of the vowel.

Fricative. A consonant produced by frictional passage of air moving through a narrowing at some point in the vocal tract; it may be either voiced (as in [v] and [z]) or voiceless (as in [f] and [s]).

Glide. A speech sound generally classified as between a vowel and a consonant, which is produced by movement or gliding to or from an articulatory position to an adjacent sound (generally a vowel); in English, the glides include /w/ and /y/ and, in some classification systems, /l/ and /r/.

Homograph. A word identical in spelling with another, but different in origin, pronunciation, or meaning.

Independent variable. The aspect of a stimulus or experimental environment that is varied systematically by the investigator in order to determine its effect on some other variable (i.e., the subject's response). For example, the investigator might systematically alter the frequency of a tone (independent variable) in order to assess the effect of these changes on the observer's auditory threshold (dependent variable). (*Compare* **dependent variable.**)

Intervocalic. Occurring between vowels.

Labial. Articulated using one or both lips (as in [b], [w]); sounds articulated using both lips are frequently termed **bilabial.**

Labiodental. Articulated with the lower lip touching the upper central incisors (as in [f], [v]).

Latency. The time between the onset of a stimulus and the beginning of the individual's response to the stimulus; also called **reaction time** or **response time.**

Lexical decision task. A task in which the subject must judge whether a given letter string is a word.

Linguadental. Articulated with the tip of the tongue placed on the upper front teeth (as in the *th* sound of *thin*).

Method of adjustment. A psychophysical method of determining a threshold in which the subject (or the experimenter) adjusts the value of the stimulus until it just meets some preset criterion (e.g., just is detectable) or until it is apparently equal to a standard stimulus.

Method of constant stimuli. A psychophysical method of determining a threshold in which the subject is presented with several fixed, discrete values of the stimulus and makes a judgment about the presence or absence of the stimulus or indicates its relation to a standard stimulus (e.g., brighter, dimmer).

Method of limits. A psychophysical method of determining a threshold in which the experimenter varies a stimulus in an ascending or descending series of small steps and the observer reports whether the stimulus is detectable or not or indicates its relation to a standard stimulus.

Palatal. Articulated with the tongue on or near the hard palate (as in [r], [ž]).

Phone. The smallest discriminable unit of sound in speech. (CRef. 8.206)

Phoneme. The smallest meaningful unit of speech; i.e., the shortest segment of speech that, if altered, alters the meaning of a word. (CRef. 8.206)

Reaction time. The time from the onset of a stimulus to the beginning of the subject's response to the stimulus by a simple motor act (such as a button press).

Retina. The membranous structure lining the inside of the eyeball which contains the photoreceptors (rods and cones) that mediate vision.

Saccade. A short, abrupt movement ("jump") of the eyes, as in shifting fixation from one point to another (such as occurs in reading).

Sensation level. The amount (in decibels) by which the level of a sound exceeds the threshold of audibility of the sound for a given listener.

Signal-to-noise ratio. The ratio of the intensity of a signal to the intensity of noise in the absence of the absence of the signal. In most auditory studies, the signal-to-noise (S/N) ratio is measured as the relative sound pressure level of the signal and noise in decibels re 20 μPa, so that an S/N ratio of zero indicates that signal and noise are of equal amplitude, while positive and negative values indicate that the signal is of greater or lesser amplitude than the noise, respectively.

Sound pressure level. The amount (in decibels) by which the level of a sound exceeds the reference level of 20 μPa (or 0.0002 dynes/cm²).

Spectrogram. A graphic record of speech in which the intensity of acoustic energy at a given frequency is plotted as a function of time. (CRef. 8.202)

Standard deviation. Square root of the average squared deviation from the mean of the observations in a given sample. It is a measure of the dispersion of scores or observations in the sample.

Standard error of the mean. The standard deviation of the sampling distribution of the mean; mathematically, the standard deviation of the given data sample divided by the square root of one less than the number of observations. It describes the variability of the mean over repeated sampling.

Stop. A consonant sound (such as [b] or [t]) whose articulation requires complete closure of the vocal tract at some point.

Threshold. A statistically determined boundary value along a given stimulus dimension which separates the stimuli eliciting one response from the stimuli eliciting a different response or no response (e.g., the point associated with a transition from "not detectable" to "detectable" or from "greater than" to "equal to" or "less than"). (CRef. 1.657) (*See also* **difference threshold**.)

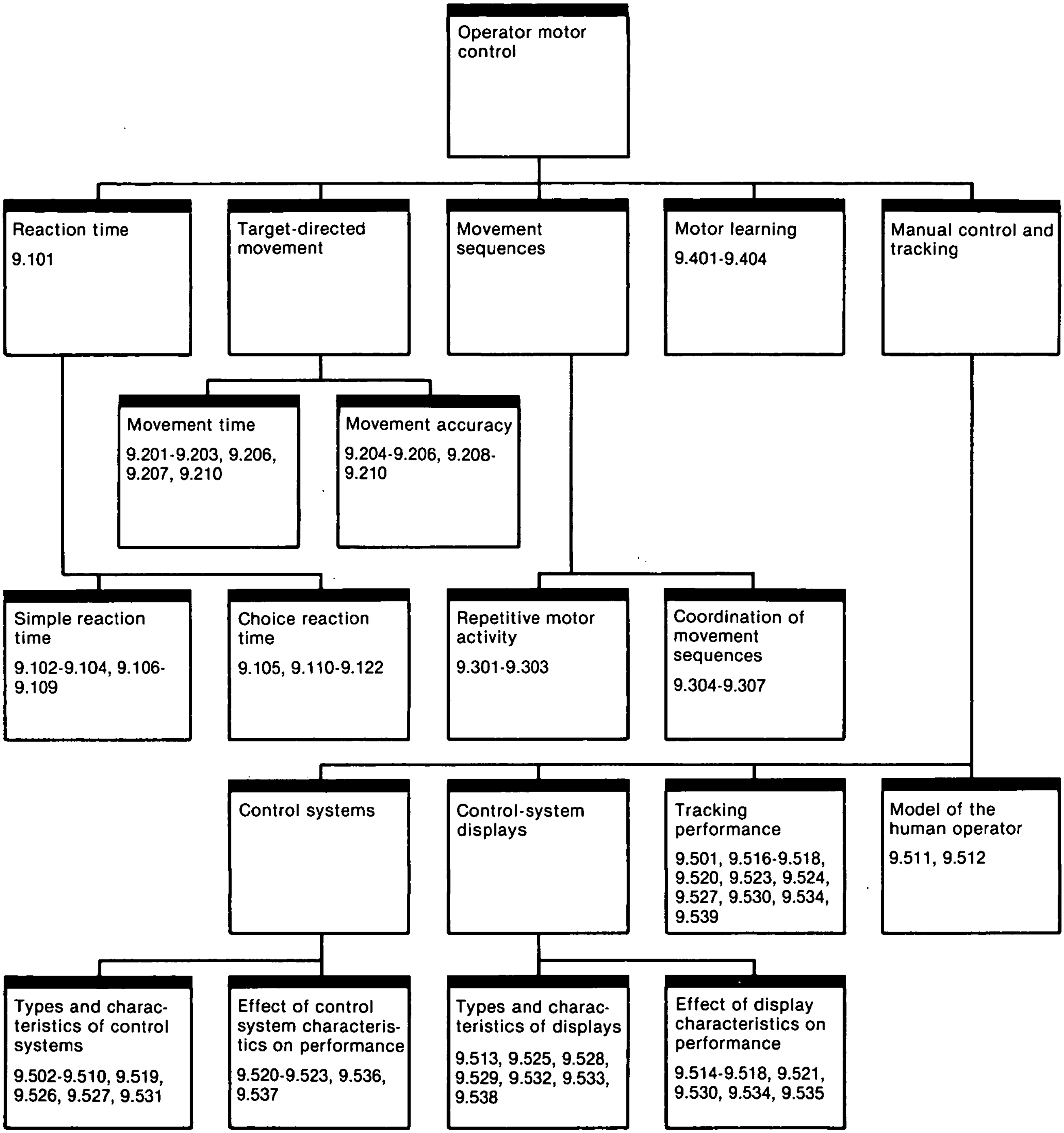
Velar. Articulated with the tongue on or near the soft palate (velum) (as in [g], [k]).

Visual acuity. The ability of an observer to resolve fine pattern detail. Acuity is usually specified in terms of **decimal acuity**, defined as the reciprocal of the smallest resolvable pattern detail in minutes of arc of visual angle. "Normal" or average acuity is considered to be 1.0 (a resolution of 1 min arc), although many young adults have a decimal acuity slightly better than this. (CRef. 1.602)

Voicing. Vibration of the vocal cords during the production of a phoneme. Phonemes accompanied by vibrations of the vocal cords (such as /b/) are voiced, and phonemes not accompanied by vibrations (such as /p/) are unvoiced.

White noise. Random noise whose spectral level (noise-power density) is uniform over a specified frequency range; termed "white noise" by analogy to white light.

Organization of Entries



Contents

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Section 9.5 Manual Control and Tracking

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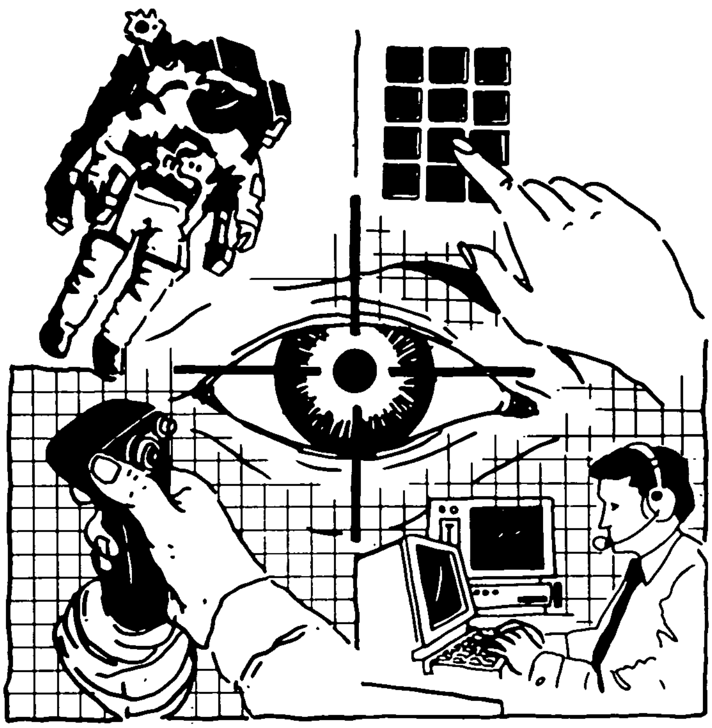
Section 9.0 Operator Motor Control



9.101 Reaction Time Tasks and Variability

Table 1. Reaction time under a variety of conditions. (From Ref. 2)

Modality	Conditions	Representative RT
Vision	Optimal	150 msec
	Candlelight	200 msec
	Small, brief, dim stimulus	500 msec
Audition	Optimal	110-120 msec
	Low intensity (30-40 dB)	150 msec
	Near threshold	350 msec
Tactile	Optimal	110-120 msec

Key Terms

Choice reaction time; disjunctive reaction time

General Description

Reaction time (RT) is defined as the time from the onset of a stimulus until the beginning of a response. Also called response latency, RT is measured only until the onset of the response to differentiate, as much as possible, the time used in decision processes from the time used to produce the response. The main thrust of RT research is to study perceptual and cognitive processes.

RT tasks are of three types: simple, disjunctive, or choice.

- In simple RT tasks, only one stimulus occurs and the subject makes only one response to that stimulus. Simple RT can be influenced by stimulus modality, intensity, or duration, and other factors (CRef. 9.108).
- Disjunctive RT tasks also require only one response to a single stimulus, but other stimuli may be presented as distractors. RTs for disjunctive tasks are generally longer than those for simple RT tasks. Disjunctive RT tasks are used to study the time necessary to make discriminations.
- Choice RT tasks, which are used most often in current research, involve multiple stimuli and multiple responses. The need to choose among a number of alternatives generally increases response time. The mapping between stimuli and responses is usually one-to-one, but other mappings are also used (CRef. 9.111). All of the factors that affect simple RT also affect choice RT, but the use of multiple stimuli and responses may introduce new factors such as unequal probability of stimulus occurrence (CRef. 9.112).

Constraints

- Representative simple RTs, listed in the table for different classes of stimuli under different conditions, show a great deal of variation. Optimal conditions include a fast, practiced subject, and the RT values for optimal conditions represent approximate minimum values.
- The RT for sensing the onset of bodily rotation is so variable that only a median (of 400 msec) can be meaningfully defined. In contrast, the RTs for touch encompass a narrow range (from 110-160 msec).
- Response times range from minimums for simple RT to much longer for choice RT in complex situations. In general, the more complex the perceptual and cognitive processes required, the longer the RT.
- Large RT differences occur both across individuals and within individuals. Simple and choice RT tasks show only a small positive correlation within individuals, and only choice RT tasks show a small positive correlation with intelligence. Some individuals decrease their RTs with practice and some do not. The RTs for people between 15 and 60 are generally faster than for people over 60, and RTs for children under 15 are generally slowest of all. Factors such as fatigue, sleep deprivation, sensory deprivation, time of day, environmental stresses, drug use, and disease can also add to an individual's RT variability (CRefs. 7.418, 7.801, 7.803, 10.202, 10.301, 10.601, 10.602, 10.704, 10.705, 10.706, 10.707, 10.708, 10.712, 10.801, 10.805, 10.808, 10.809).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Keele, S. W. (1986). Motor control. In K. R. Boff, L. Kaufman, and J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance*. New York: Wiley.

2. Postman, L., & Egan, J. (1949). *Experimental psychology: An introduction*. New York: Harper.

3. Woodworth, R. S. (1938). *Experimental psychology*. New York: Henry Holt.

Cross References

7.418 Sex differences in vigilance performance;

7.801 Effect of incentives on performance;

7.803 Effect of anxiety on performance;

9.108 Factors affecting simple reaction time;

9.111 Choice reaction time: effect of number of alternatives;

9.112 Choice reaction time: effect of probability of alternatives;

10.202 Effects of different stressors on performance;

10.301 Noise bursts: effect on task performance;

10.601 Heat: effect of exposure duration on task performance;

10.602 Cold: effect on performance;

10.704 Time of day: effect on memory;

10.705 Time of day: effect on short-term memory and speeded decision making;

10.706 Time of day: effect on speeded decision making;

10.707 Circadian variation in work efficiency;

10.708 Incentive and introverted/extroverted personality; effect on the diurnal rhythm of performance;

10.712 Schedule shift: effect on performance;

10.801 Fatigue: effect on performance;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.808 Sleep deprivation: effect on circadian rhythm;

10.809 Partial deprivation of sleep: effect on performance

9.102 Simple Reaction Time to Visual Targets of Different Luminances

Key Terms

Photopic vision; Piéron's law; Ricco's law; scotopic vision; spectral distribution; visual latency

General Description

The manual reaction time (RT) of a dark-adapted observer varies as a function of flash intensity (luminance). RT can be broken into two components: a portion (T_∞) that is not a function of luminance, and a portion ($RT - T_\infty$) that is. The equation (Piéron's Law) relating RT and luminance (as intensity I in dB) in Fig. 1 is

$$RT = T_\infty + kI^\beta$$

k is a scaling constant; β is an exponent that depends on target size; and I is in dB with 1 dB = 10 log (I/I_0), where I_0 denotes a reference level of $\pi^{-1} \times 10^{-6}$ cd/m^2.

β usually ranges from −0.33 for large (i.e., extended) targets to −0.5 for small targets within Ricco's area of spatial summation (Ref. 2). To a first approximation, β is independent of retinal locus, spectral composition, and flash duration. Furthermore, the RT functions for photopic (cone = mediated) and scotopic (rod = mediated) retinal processes are similar, differing by only 40 msec at asymptote. For photopic processes and for any given RT, luminance increases with increasing distance from the fovea. For scotopic processes, the required luminance decreases out to 20 deg from the **fovea,** and then begins to increase.

For brief flash durations, RT is determined by stimulus energy rather than stimulus luminance; the exponent for the energy function is identical to that of the luminance function for longer durations. When luminance is held constant, RT is inversely related to flash durations up to durations of ~10 msec, but is independent of duration for longer flashes (Figs. 2a,b).

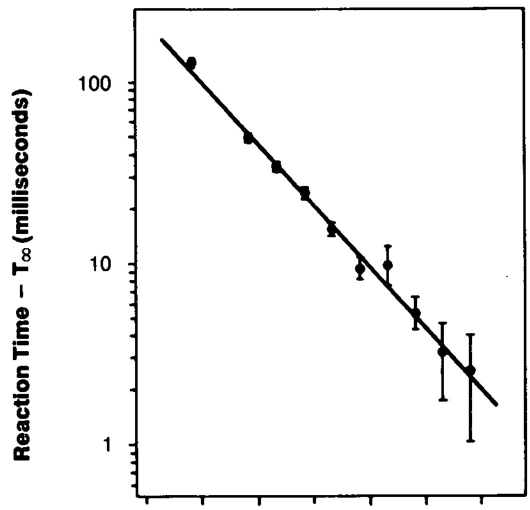


Figure 1. Intensity-dependent component of reaction time (RT), calculated as $RT - T_\infty$, as a function of stimulus luminance. The straight line is Piéron's Law and maximizes Pearson r^2 with T_∞ = 194.9 msec and β = −0.329. The vertical bars indicate standard errors. (From Ref. 2)

Methods

Test Conditions

- Square wave flashes of white or monochromatic light as targets; 108.5 dB and 101.4 dB unfiltered white light provided by 4-W and 14-W lamps, respectively; intensity controlled by Wratten neutral-density filters; five narrow spectral bands of monochromatic light (maximum half-power bandwidths ≤ 13 nm; peak transmittances at 453, 480, 502, 577, or 629 nm)
- Fixation on a small (0.08 deg), dim, red lamp located either at center of target (extended-source target) or placed to right of target (extended target), or fixation point between two lamps ~4 deg on each side of target (point-source target)
- Extended target viewed only with right eye; extended-source and point-source targets viewed binocularly
- Observer dark-adapted for minimum of 15 min prior to session
- Interflash interval varied from 2.5-5.0 sec (3.31-sec average); at least 1-min rest period between blocks of 30 trials each
- Stimulus repeated (blocked) until 25 RTs obtained; subthreshold defined as when >20% of flashes undetected in a block; blocks of supra-threshold flashes repeated if >2 misses in 25 trials occurred
- Binaural white noise presented to mask experimental sounds

Experimental Procedure

- Independent variables: spectral composition (white or monochromatic light), target size, retinal locus of target (foveal or peripheral), flash intensity (luminance)
- Dependent variable: reaction time
- Observer's task: release switch immediately upon detection of light flash
- 2 observers with normal or corrected vision with extensive practice

Experimental Results

- Mean RTs for peripheral and some foveal targets (i.e., those impinging upon rod-bearing regions) exhibit both fast and slow response components. Fast-response components are attributable to photopic (diurnal or "bright light," cone-based) vision, whereas slow reaction components are associated with scotopic (rod-based, nocturnal or "dim light") visual processes.
- In general, least-squares regression (correlation) analysis (e.g., Fig. 1) indicates that the data can be fitted by Piéron's Law

$$RT - T_\infty = kI^\beta.$$

T_∞ denotes the minimal (asymptotic) RT (in msec) to brightly illuminated stimuli; k is an empirically derived scaling factor that differs for photopic and scotopic mecha-

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nisms; *I* represents the flash intensity or luminance of the visual stimulus; and β is an empirically determined exponent that generally ranges from −0.31 to −0.33 for all but point-source targets (for which β = −0.5).

• When the visual stimuli presented are brief (0.3-10 msec), RT is primarily determined by the energy of the flash (in cd-sec/m^2) rather than its intensity or luminance (in cd/m^2). However, for "long" flashes (30-300 msec), RT is a function of luminance or flash intensity (Fig. 2).

Variability

Observers exhibited large individual differences in RT and long-term "drifts" in task performance. However, the intensity-dependent RT component (Fig. 1) did not show this variability.

Repeatability/Comparison with Other Studies

Other studies (e.g., Refs. 3, 4) have reported similar results.

Constraints

Piéron's Law was determined for manual reactions, not for eye movements.

Key References

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*2. Mansfield, R. J. W. (1973). Latency functions in human vision. *Vision Research, 13*, 2219-2234.

3. Piéron, H. (1952). *The sensations*. New Haven, CT: Yale University Press.

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Cross References

9.108 Factors affecting simple reaction time;

11.406 Visual warning signals: effects of background color and luminance;

11.409 Visual warning signals: effect of size and location;

Handbook of perception and human performance, Ch. 10

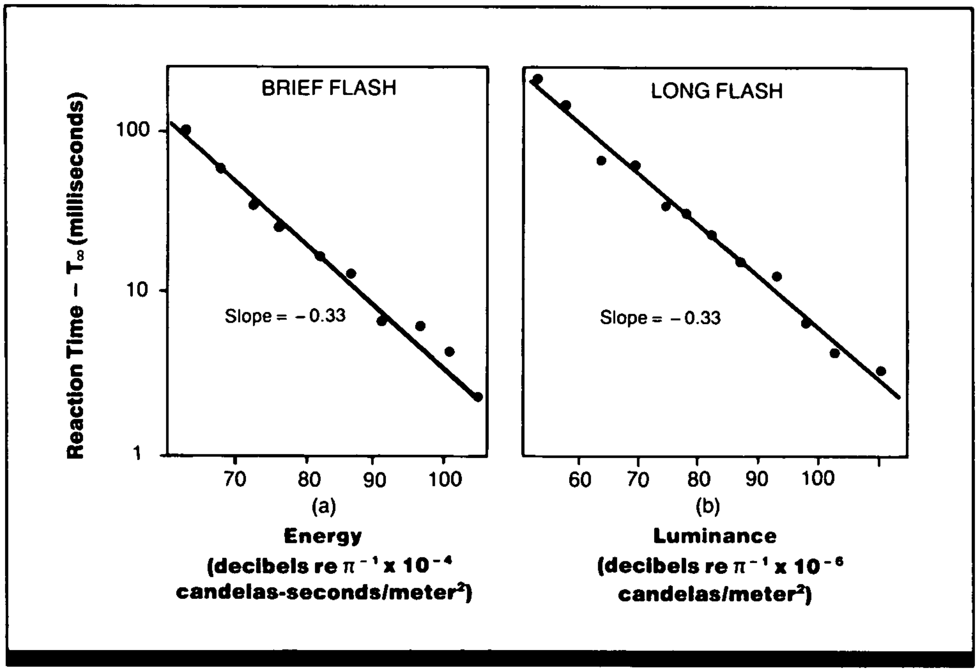

Figure 2. Intensity-dependent component of RT for (a) short (0.3, 1.0, 3.0, and 10.0 msec) and (b) long (30, 100, and 300 msec) flashes of white light. Foveal target subtended 0.72 deg. (From Ref. 2)

9.103 Simple Reaction Time: Effect of Target Spatial Frequency (Size) and Contrast

Key Terms

Contrast; size

General Description

Visual **reaction time** to a **sine-wave grating** (bar pattern) varies with the **spatial frequency** (bar size) and contrast of the grating target. Observers have increasingly shorter reaction times to gratings with increasingly lower spatial frequency. Reaction time is slightly improved when the grating is of high contrast.

Methods

Test Conditions

- Sine-wave gratings presented on CRT; 23 cd/m^2 mean screen luminance; 2.3 mm-diameter artificial pupil; only right eye used
- Grating was 5.3 deg of visual angle wide, 3.8 deg high
- Dark surround; **foveal** presentation; 100 msec exposure duration; microswitch kept in right hand and operated with thumb; acoustic warning signal preceded grating by 1370 to 2210 msec
- Spatial frequencies of grating: 1, 1.7, 5.3, or 16 cycles/deg
- Contrast of grating: 3, 4.5, or 6 times threshold, which was taken as 50% point of yes/no frequency-of-seeing curve
- Twenty-five trials for each combination of spatial frequency and contrast value

Experimental Procedure

- Independent variables: spatial frequency of grating, contrast of grating
- Dependent variable: reaction time in msec
- Observer's task: operate microswitch as quickly as possible after seeing pattern
- 3 experienced observers

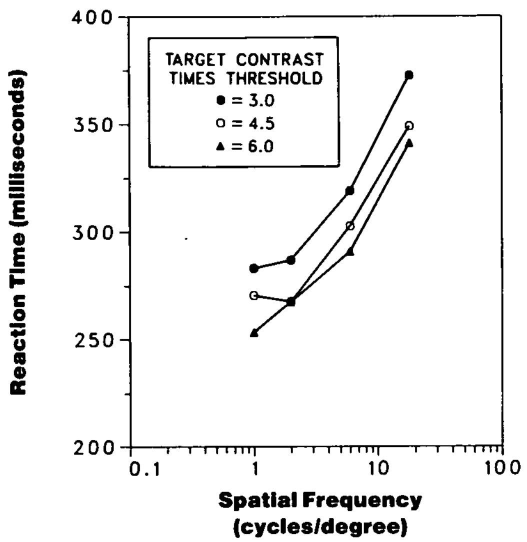

Figure 1. Reaction time to sine-wave gratings as a function of spatial frequency for targets of various contrasts. (From Ref. 2)

Experimental Results

- Reaction times are longer to sinusoidal gratings of high spatial frequency than to gratings of low spatial frequency. For example, reaction time is roughly 90 msec longer for a 16 cycle/deg grating than for a 1 cycle/deg grating.
- Lowering the contrast of a grating, but keeping it well above detection threshold, increases reaction time slightly, but does not alter the dependence of reaction time on spatial frequency.

Variability

- There is considerable variability in reaction times between observers and within one observer from trial to trial. Reported range for one observer was 240 msec to 440 msec in one session for a grating with a spatial frequency of 1 cycle/deg.

Repeatability/Comparison with Other Studies

- Reference 1 also found longer reaction times for high- than for low-frequency gratings of equal apparent contrast. Reference 3 found that reaction times to near-threshold gratings of medium frequency (3.5 cycles/deg) had a unimodal distribution, whereas reaction times to low-frequency gratings were bimodal because observers responded either to onset or offset of stimulus.

Constraints

- Many factors, such as practice, exposure duration, and number of alternative stimuli and responses, can influence reaction times and must be considered in applying these results to other viewing conditions (CRef. 9.109).
- Many factors, such as target orientation and luminance level, affect the visibility of gratings and might therefore be expected to affect reaction time to grating targets (CRefs. 1.603, 1.628).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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*2. Lupp, U., Hauske, G., & Wolf, W. (1976). Perceptual latencies to sinusoidal gratings. *Vision Research, 16,* 969-972.

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Cross References

1.603 Factors affecting visual acuity;

1.628 Factors affecting contrast sensitivity for spatial patterns;

9.108 Factors affecting simple reaction time;

9.109 Simple reaction time to visual targets

9.104 Attentional Limitations in Reaction Time Tasks

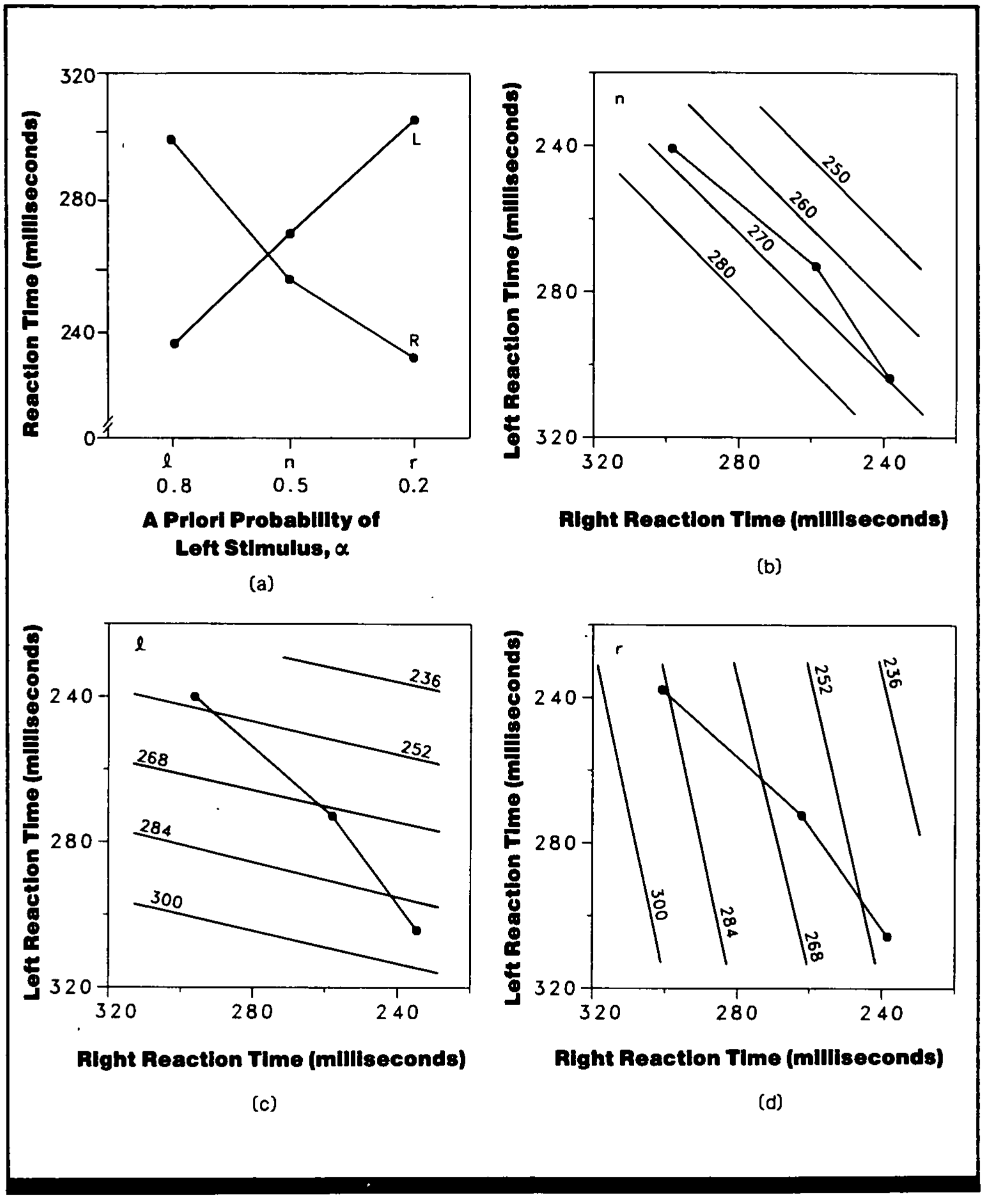

Figure 1. Reaction times to stimuli with different *a priori* stimulus probabilities. All panels illustrate the same data from Ref. 1. (a) Mean reaction time in msec for three *a priori* probabilities of the left stimulus as indicated by the warning cue. Stimulus was either left (L) light or right (R) light. In panels (b), (c), and (d), the data of (a) are regraphed as performance operating characteristic curves. The iso-utility contours represent the mean reaction times indicated on the contour; each point along a contour represents a joint reaction-time performance to left and right stimuli; the overall mean reaction time is the *u* value shown on the contour, $u = \alpha RT_L + (1 - \alpha) RT_R$, where α = probability of left stimulus, and RT_L and RT_R = reaction time to left and right stimuli, respectively. The iso-utility contours represent a weighting of performance appropriate to the stimulus probabilities for the conditions. (b) Neutral cue *n*, $\alpha = 0.5$; (c) left cue *l*, $\alpha = 0.8$: (d) right cue *r*, $\alpha = 0.2$. (From Ref. 3)

Key Terms

Attention; decision making; detection; expectancy; speed-accuracy tradeoffs; uncertainty

General Description

Reaction time is shorter when a light flashes in a high-probability location than in a low-probability location. One theoretical explanation of this divided attention effect is that input at the more probable location receives more coding. A second explanation argues that criterion shifts in the decision process, not enhanced perception, are responsible for the finding (CRef. 7.219).

Applications

Tasks involving divided visual attention.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Visual display with fixation point between two possible stimulus locations
- Target was 0.2 deg light flash appearing 6.9 to left or right of fixation point
- 1 sec prior to light flash, observer informed by onset of left or right arrow about probability of left light flashing, α; α was 0.20, 0.50, or 0.80 on any trial

Experimental Procedure

- Choice reaction time task
- Independent variable: probability of left light flashing
- Observer's task: press key as soon as flash appeared
- Highly practiced observers

Experimental Results

- Mean reaction time is 60 msec shorter when the target is in the high-probability location than in the low-probability location.
- When data are replotted as **performance operating characteristics** (POC) curves (CRef. 7.205) with coordinates representing reaction times to left and right stimuli respectively, they can be fitted with three sets of iso-utility contours, which weigh performance by different probabilities.
- Replotted data indicate that when two stimuli are equally probable, weighted reaction times for both flashes fall on the iso-utility curve for 270 msec; when either the left or right stimulus is more probable, reaction times fall on different iso-utility curves, showing that there is a tradeoff between short reaction times for more probable stimuli and long reaction times for less probable stimuli.
- Iso-utility and POC analyses support the claim that divided attention alters performance because of criterion shifts in the decision process, while traditional reaction time analysis supports the theoretical position that divided attention alters performance because of enhanced perceptual coding (CRef. 7.219).

Variability

No information on variability was given.

Constraints

- Many factors, such as probability of target, practice, and warning period duration, can influence reaction time and must be considered in applying these results to other testing conditions.

Key References

*1. Posner, M. L., Nissen, M. J., & Ogden, W. C. (1978). Attended and unattended processing modes: The role of set for spatial location. In H. L. Pick Jr. & E. Saltzman (Eds.), *Modes of perceiving and processing information*. Hillsdale, NJ: Erlbaum.

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Cross References

7.205 Performance operating characteristic;

7.219 Division of attention among spatial locations;

7.221 Attentional and decision-making factors in component and compound tasks;

9.101 Reaction time tasks and variability;

9.105 Speed-accuracy tradeoffs

9.105 Speed-Accuracy Tradeoffs

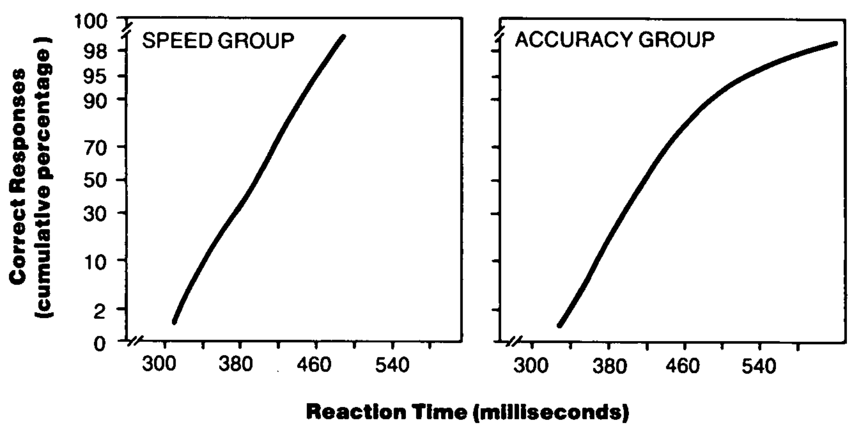

Figure 1. Speed-accuracy tradeoff, with curves based on 2400 correct responses of 6 highly practiced observers, tested on a reaction time task containing ten possible visually presented stimulus alternatives. (Adapted from Ref. 2)

Key Terms

Attention; choice reaction time; expectancy; memory; response speed; speed-accuracy tradeoffs; uncertainty

General Description

In many human performance tasks, a tradeoff exists between the speed of a response and its accuracy—quicker responses are more likely to be wrong than are slower responses, and reaction time becomes longer when observers are instructed to be more accurate. Observers rewarded for quick rather than accurate responses show different reaction times than observers rewarded for accurate rather than quick responses, as shown in Fig. 1.

Several experiments demonstrate that the tradeoff between speed and accuracy is orderly and predictable and that observers can be trained to adjust the speed of their responses to meet specified accuracy requirements. Two methods have been developed to alter an observer's responding: the deadline method and the cued response method. In the deadline method, the observer is instructed to make all responses within a specified time after stimulus onset, and, with training, can do so. In the cued response method, the observer is to emit a response as fast as possible after a secondary cue, which follows the stimulus after a variable interval. Small changes in accuracy may be accompanied by large changes in reaction time.

The speed-accuracy tradeoff has been demonstrated in a choice reaction time task using 10 stimulus alternatives (Ref. 2), in an absolute judgment experiment regarding the location of a vertical bar that could assume one of two, four, or eight positions (Ref. 3), in a recognition memory study measuring the time to retrieve sentences from semantic memory, and in many other tasks.

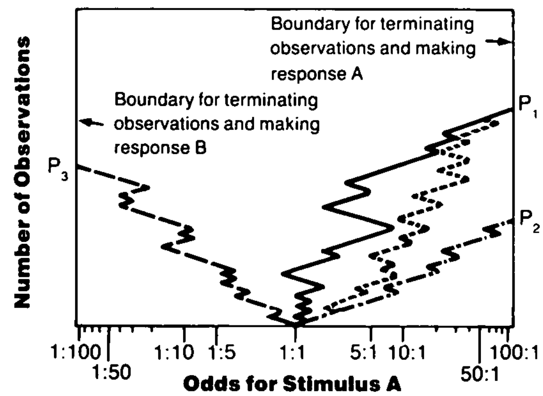

Figure 2. Random-walk model of choice reaction time. P_1, P_2, and P_3 are thresholds of information; the four traces represent different "walks," or ways in which an observer might reach a threshold. (From Ref. 2)

A **random walk model** of speed versus accuracy postulates an ideal observer who accumulates information about two possible alternative responses; when information exceeds some threshold, a response is made. The cumulative balance of information is said to waiver between the alternatives, thus constituting a random walk. The observer continues to gather information until some boundary is reached; strategy includes choosing response threshold (the distance from a starting point to either absorbing boundary) for each alternative. (See Figs. 2 and 3.)

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Constraints

• Many factors, such as practice effects, payoff matrices, and conditions for evoking a response can influence performance and must be considered in comparing results in different studies and for applying them to different experimental situations.

Key References

1. Dosher, B. A. (1976). The retrieval of sentences from memory: A speed-accuracy study. *Cognitive Psychology, 8,* 291-310.

2. Fitts, P. M. (1966). Cognitive aspects of information processing: III. Set for speed versus accuracy. *Journal of Experimental Psychology, 71,* 849-857.

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Cross References

9.109 Simple reaction time to visual targets

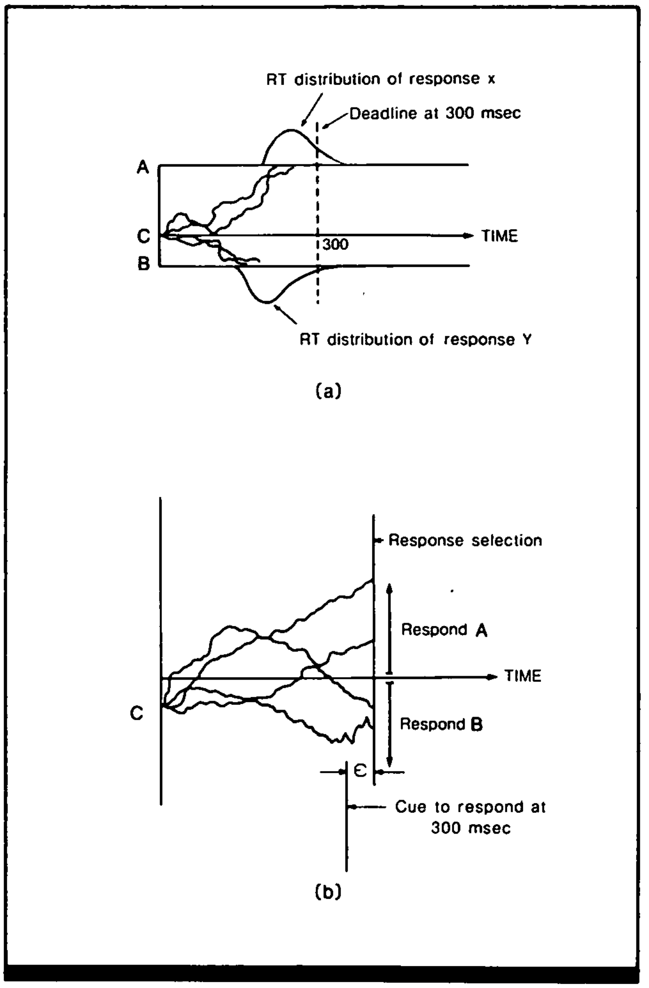

Figure 3. Random walk models for two speed-accuracy tradeoff procedures. (a) The deadline procedure. The value of the random walk is plotted for time, *t*. Several representative walks are shown. *C* is the starting point for the walk and indicates that Stimulus *B* is much more probable than Stimulus *A*. The random-walk boundaries (*A* and *B*), corresponding to the two stimulus alternatives, are set by the subject (after some training) so that very few responses exceed the 300-msec deadline. (b) The cued response procedure. The boundaries, *A* and *B*, are absent, and the response is determined by the location of the walk at the time of the cue. (From Ref. 4)

9.106 Reaction Time: Effect of Uncertainty

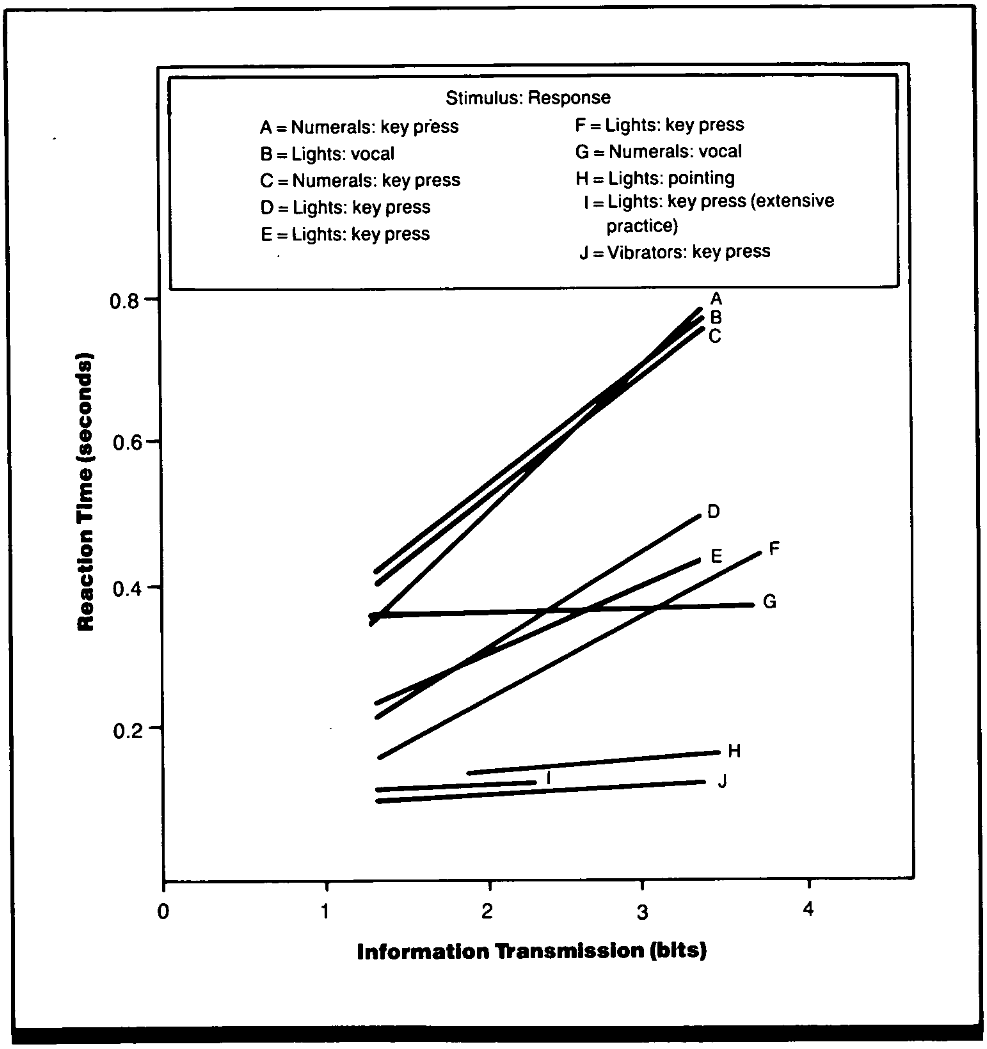

Figure 1. Reaction time as a function of information transmission (= $\log_2$ number of alternative choices) for various stimulus-response conditions. (From Ref. 2)

Key Terms

Decision making; discrimination; information transmission; response differentiation; uncertainty; vigilance; warnings

General Description

As subjects are required to respond under higher degrees of uncertainty in a choice reaction time task (i.e., number of stimuli or response alternatives increases), their rate of responding slows proportionately to the increase in information transmission. (The information transmitted, under ideal conditions, is equal to the uncertainty, H, in bits associated with the number of alternatives, n, computed as $H = \log_2 n$ [CRef. 4.301]). The increase in reaction time varies, depending on the task. Figure 1 illustrates the results from a number of studies. In all cases, the relationship between reaction time and information transmission in bits can be best described by a straight line. However, the slopes of the lines vary, primarily due to the degree of compatibility between stimulus and response codes. For example, Curves *G* (Ref. 5) and *J* (Ref. 4) represent largely simple stimulus-response tasks. By contrast, Curves *F* (Ref. 3) and *B* (Ref. 1) represent situations in which larger numbers of stimulus discriminations or response differentiations were required. An additional factor which may affect the slope of the line is practice. Over time, practice tends to reduce the slope, particularly where a great deal of uncertainty is inherent in the task.

Empirical Validation

Although no statistical analyses have apparently been conducted, the complete concurrence of the data reported in Fitts and Posner (Ref. 2) lends credence to the validity of this principle.

Constraints

• The studies illustrated in Fig. 1 all involved up to 10 alternatives or 3.3 bits of information. Above this range, no simple relationship between reaction time and information can be postulated.

• The relationships shown here are for initial estimates and general guidance only. Each application is unique and should be subject to verification, particularly where time-critical performance is required.

Key References

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3. Hick, W. E. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology, 4*, 11-26.

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Cross References

4.301 Information theory;

7.102 Human reliability analysis;

7.401 Vigilance;

7.404 Reaction time patterns in vigilance performance;

9.108 Factors affecting simple reaction time;

9.111 Choice reaction time: effect of number of alternatives;

12.301 Principles of grouping and arranging controls;

12.302 Guidelines for control/display position and movement relationships;

12.303 Recommended minimum distances between controls;

12.304 Military aviator reach envelopes for placement of controls

9.107 Serial Reaction Time: Effect of Signal Spacing

Key Terms

Psychological refractory period; serial reaction time; warnings

General Description

When two signals (*S*1 and *S*2) are presented in rapid succession and each requires a response, the reaction time (RT) to the second (RT2) is longer than the RT when the second signal is presented alone. This psychological refractory period is most evident when the time between the onsets of *S*1 and *S*2 is less than the time needed to respond to *S*1 (RT1). When the time between *S*1 and *S*2 is longer than the time for the response to *S*1, RT2 is relatively normal. Increasing the number of alternatives for the first stimulus (*S*1) results in increased RTs to *S*1 and therefore causes an increased RT2 (Fig. 1). Increasing the number of possible stimuli for *S*2 increases RT2, and also causes a small but consistent increase in RT1.

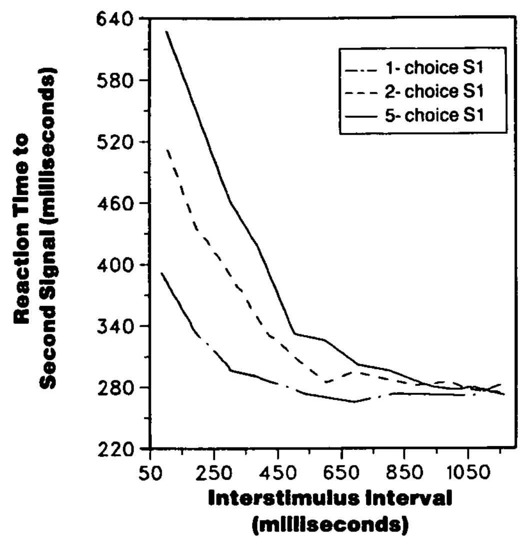

Figure 1. Reaction time to a second signal as a function of interstimulus interval and number of alternatives for the first signal. There were two alternatives for *S*2. (From Ref. 5)

Methods

Test Conditions

- RT task with varied number of alternative stimulus-response pairs for *S*1 and *S*2 (5-2, 2-2, 1-2, 2-1, and 1-1 for *S*1-*S*2)
- *S*1 was one, two, or five digits from 1-5 flashed by a Nixie tube seen through a Polaroid filter for 35 msec; *S*2 stimulus was a 35-msec tone of either 600 or 3000 Hz presented through headphones
- *S*1 responses were button presses by left hand with little finger assigned to the number 1 and other fingers assigned to buttons in order; *S*2 responses were button presses by either index (for high tone) or middle finger (for low tone) of right hand
- 40-msec warning tone of 1000 Hz presented 1.7, 1.9, 2.1, or 2.3 sec before *S*1; interstimulus intervals of 90, 190, 290, 390, 490, 590, 690, 790, 890, 990, 1090, or 1190 msec; intertrial interval of 5 sec

Experimental Procedure

- Independent variables: number of alternatives, length of interstimulus interval
- Dependent variables: RTs for *S*1 and *S*2
- Subject's task: press correct button with left hand for *S*1; press correct button with right hand for *S*2 (tone); no feedback given
- Trials yielding highly deviant RTs were dropped from the analysis (~6% of trials for one subject and ~3% for other subjects)
- 6 subjects with extensive practice

Experimental Results

- Increasing the number of *S*1 alternatives (1, 2, or 5) causes a large increase in RT1; increasing the number of *S*2 alternatives (1 or 2) causes a slight increase in RT1.
- RT1 is independent of interstimulus interval.
- Increasing the number of *S*1 alternatives increases RT2 when the interstimulus interval is <~900 msec.
- Increasing the number of *S*2 alternatives increases RT2.

Variability

Each subject's performance is well represented by the overall means in most instances. The data for one subject were dropped because of excessively long and irregular RTs.

Repeatability/Comparison with Other Studies

The psychological refractory period (PRP) has been demonstrated repeatedly (for a review see Ref. 1). The PRP decreases but does not disappear with practice; PRPs still occur for time intervals other than the specific interval that was practiced (Ref. 3). It has been difficult to devise an experiment that eliminates the PRP at interstimulus intervals of <200 msec (Ref. 4); of four conditions, only the one having highly compatible stimulus-response pairings with two stimuli and two responses in different sensory modalities (visual *S*1 and manual *R*1, auditory *S*2 and vocal *R*2) did not show the PRP effect. The *S*1-*R*1 condition required the subject to move a switch in the direction indicated by an arrow and under the *S*2-*R*2 condition, subject stated spoken word ("one" or "two").

Constraints

- There are numerous theoretical explanations for the PRP, but no definitive statement can be made about the mechanisms involved.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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*5. Karlin, L., & Kestenbaum, R. (1968). Effects of number of alternatives on the psychological refractory period. *Quarterly Journal of Experimental Psychology, 20*, 167-178.

Cross References

9.108 Factors affecting simple reaction time;

9.111 Choice reaction time: effect of number of alternatives;

9.115 Choice reaction time: effect of stimulus-response compatibility on error;

Handbook of perception and human performance, Ch. 30, Sect. 1.3

9.108 Factors Affecting Simple Reaction Time

Key Terms

Expectancy; motivation; uncertainty

General Description

Simple reaction time (RT) occurs when there is only one possible stimulus and only one designated response; for example, an observer presses a control button whenever a light goes on. The limitation of only one stimulus-response pair differentiates simple RT from choice RT, which has either a set of possible stimuli or a set of possible responses, or both. Simple RT will vary from observer to observer because of individual differences (e.g., the time necessary for nerve impulses to begin movement of the hand). Other factors, listed in the table, also affect simple RT.

Factor	Effects
Modality	Reaction time (RT) for auditory stimuli are often faster than RT for visual stimuli, but these differences disappear when intensity is appropriately equated between the modalities. (CRef. 9.101)
Location in field of view	RT for foveal vision is somewhat shorter than RT for the same stimulus in peripheral vision; the difference between RTs for foveal and peripheral vision are greater when the observer (operator) has a heavy workload
Temporal uncertainty	RT is short when the time of occurrence of the stimulus is highly predictable (e.g., when a warning cue always occurs at a fixed, short interval prior to the stimulus). RT increases as the occurrence of the stimulus becomes less predictable (e.g., with variable or long warning intervals, up to an asymptote). One exception to long RT for long warning intervals is when short and long warning intervals are mixed in the same block of trials; then expectancy increases as time passes and long warning intervals yield fast RTs
Perceptual characteristics of the stimulus	RT decreases to an asymptote as factors that make the stimulus more salient increase. For example, increasing intensity, contrast, or size of a visual signal willl decrease RT (CRefs. 9.102, 9.103). These factors also interact with other stimulus characteristics; for example, when illumination is low, salience is increased more by intermittent presentation (i.e., flashing) than when illumination is high. There are also differences among RTs for different attributes that belong to the same stimulus dimemsion; for example, RTs for red or blue lights are slightly longer than for a green light
Mode of response	RT is somewhat faster with the preferred hand than with the other hand, and response with a foot is much slower than with either hand
Motivation	Increasing an observer's motivation can decrease RT, within limits
Fatigue	RT will typically increase as fatigue increases
Response device	RT varies across different types of response devices (i.e., some types of responses begin more quickly than other types of responses). For example, amount of practice, transfer of training, or stimulus-response compatibility may make a particular device easier to manipulate for a response

Key References

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Cross References

9.101 Reaction time tasks and variability;

9.102 Simple reaction time to visual targets at different luminances;

9.103 Simple reaction time: effect of target spatial frequency (size) and contrast;

9.106 Reaction time: effect of uncertainty;

9.109 Simple reaction time to visual targets

9.109 Simple Reaction Time to Visual Targets

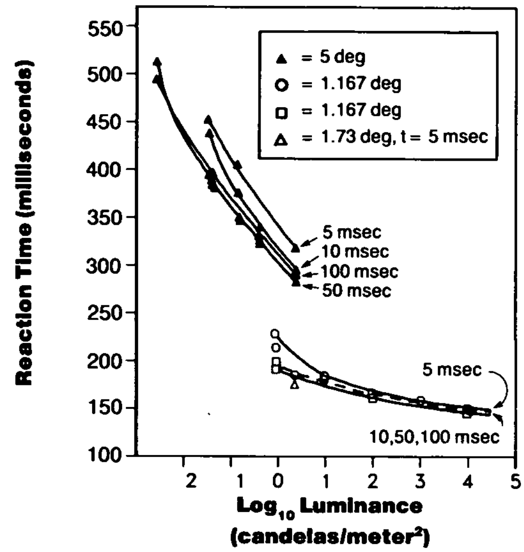

Figure 1. Reaction time to spots of light as a function of stimulus luminance, duration, and size. (From Ref. 3)

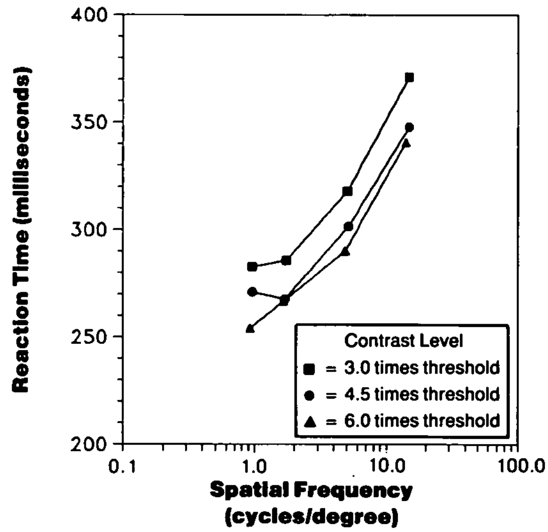

Figure 2. Reaction time to sinusoidal gratings as a function of spatial frequency and contrast level. (From Ref. 1)

Key Terms

Contrast sensitivity

General Description

When the appearance of a spot of light signals a single response and the location of that stimulus is known in advance, the reaction time (RT) for the response decreases as stimulus luminance (intensity), size, or duration increases (Fig. 1). Of the three factors, intensity has the greatest effect.

When the visual stimulus is a vertical-bar grating, RT decreases as spatial frequency decreases and stimulus duration increases. RT also decreases when the contrast between the light and dark portions of a grating (i.e., modulation) is increased (Fig. 2).

Methods

Test Conditions

Stimulus: spot of light (14 studies)

- Luminance of −3 to +4 $\log_{10}$ cd/m^2; durations of 5-100 msec (Fig. 1); targets of 0.5 deg foveal size and 1.167 and 1.73 deg extrafoveal sizes (Fig. 1); other durations and sizes studied; target location known by subject; central vision with binocular presentation; time interval between warning signal and stimulus presentation either fixed, or subjects were highly practiced in random-interval presentations

Stimulus: sinusoidal grating (3 studies)

- Spatial frequencies from 1-16 cycles/deg; durations 30-200 msec; contrast levels 3-6 times above threshold with threshold individually determined for each spatial frequency
- Grating displayed on an x-y display at 1000-Hz frame frequency; foveal presentation at angle of 5.3 deg horizontally and 3.8 deg vertically; surrounded by dark areas
- Average luminance was 48 cd/m^2 and reduced to 23 cd/m^2 with optical apparatus connected to 2.3-mm diameter artificial pupil; screen modulation linear up to 70% contrast
- After warning tone, subject pressed a key to indicate readiness; grating displayed after random delay >1370 msec
- Subject fixated small black dot in center of screen with right eye; subject's head fixed in place with bite board and headrest
- Random sequence of 320 gratings for each session; session lasted ~40 min and subjects were not fatigued at end of session

Experimental Procedure

Stimulus: spot of light

- Studies included in review only if they met the test conditions and the procedure and experimental design provided unconfounded data
- Independent variables: target luminance, duration, and size
- Dependent variable: reaction time
- Subject's task: detect stimulus and respond
- Number of subjects not reported

Stimulus: sinusoidal grating

- Independent variables: spatial frequency, contrast, duration
- Dependent variable: RT, measured as time from stimulus onset until thumb of right hand threw microswitch
- Subject's task: press button when grating is detected
- Number of subjects not reported, some practice

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

Stimulus: spot of light (Fig. 1)

- RT decreases with increases in stimulus luminance, duration, and area.
- RT is near minimum, slightly less than 200 msec, for near-threshold stimuli (cone vision) regardless of stimulus duration or size (open geometric symbols near 0 log luminance in Fig. 1).

Stimulus: sinusoidal grating (Fig. 2)

- RT increases with increasing spatial frequency at all contrast levels; difference in RT from low to high frequencies (1-16 cycles/deg) ranges from 60-80 msec.
- Gratings with lower contrast yield somewhat longer RTs than gratings with higher contrast.
- RTs are shortest for exposure durations from 30-60 msec, and the effects of differences in spatial frequency are relatively small within this range of durations.

Variability

Within- and between-subject variabilities are high, which is normal for RT studies.

Repeatability/Comparison with Other Studies

The relationship between intensity and RT has been demonstrated for other modalities as well as vision (CRef. 9.108).

Constraints

- RT results can be influenced by other parameters such as uncertainty about when the signal will occur, and by location of the signal on the retina or in the visual field (Ref. 2; CRef. 9.108)

Key References

*1. Lupp, U., Hauske, G., & Wolf, W. (1976). Perceptual latencies to sinusoidal gratings. *Vision Research, 16*, 969-972.

2. Teichner, W. H. (1954). Recent studies of simple reaction time. *Psychological Bulletin, 51*, 128-149.

*3. Teichner, W. H., & Krebs, M. J. (1972). Laws of the simple visual reaction time. *Psychological Review, 79*, 344-358.

Cross References

9.101 Reaction time tasks and variability;

9.102 Simple reaction time to visual targets of different luminances;

9.103 Simple reaction time: effect of target spatial frequency (size) and contrast;

9.108 Factors affecting simple reaction time;

Handbook of perception and human performance, Ch. 30, Sect. 1.1.

9.110 Factors Affecting Choice Reaction Time

Key Terms

Choice reaction time; warnings

General Description

Choice reaction time (RT) tasks differ from simple RT tasks in that more than one stimulus and/or response can occur. Although all the factors (e.g., sensory modality, uncertainty about when a stimulus will appear) that influence simple RT (CRef. 9.108) also affect choice RT, additional factors apply only to choice RT tasks; for example, uncertainty about which stimulus will appear and/or which response will be required. As with simple RT, choice RT is measured from stimulus onset to the initiation of the response, so that RT does not include movement time. The table lists factors that can be manipulated in choice RT tasks, states their effect on RT, and lists relevant sources or other entries.

Constraints

- The factors listed here interact not only with each other, but with factors affecting simple RT tasks, individual differences, and environmental variables.

Key References

*1. Keele, S. W. (1986). Motor control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance* (Chap. 30). New York: Wiley.

2. Woodworth, R. S. (1938). *Experimental psychology.* New York: Holt, Rinehart & Winston.

Cross References

9.101 Reaction time tasks and variability;

9.107 Serial reaction time: effect of signal spacing;

9.108 Factors affecting simple reaction time;

9.111 Choice reaction time: effect of number of alternatives;

9.112 Choice reaction time: effect of probability of alternatives;

9.113 Choice reaction time: effect of stimulus probability and response-stimulus interval;

9.114 Choice reaction time: effect of warning interval on error;

9.115 Choice reaction time: effect of stimulus-response compatibility on error;

9.116 Choice reaction time: effect of stimulus-response compatibility;

9.117 Choice reaction time: detection of targets amid irrelevant stimuli;

9.118 Choice reaction time in the presence of conflicting information;

9.120 Reaction time for coupled manual and vocal response: effect of stimulus probability;

9.121 Interaction among multiple stimuli and responses;

11.420 Response time with redundant information

Table 1. Factors affecting choice reaction time.

Factor	Description	Effect	References
Stimulus-Response (S-R) Characteristics			
Number of S-R pairs	Choice RT tasks can incorporate any number of S-R pairs; 10 is usually the maximum	Each additional S-R alternative increases RT, but each succeeding additional S-R pair adds less to RT than the previous pair	CRef. 9.111
		Each doubling of alternatives adds ~150 msec to RT	Ref. 1
		RT can range from 187 msec for simple RT to 622 msec for ten S-R pairs, depending on modality	
Probability	Increasing the number of S-R pairs decreases probability of occurrence of each pair; probabilities for S and R can be varied independently	High-probability S and R generate shorter RT	CRefs. 9.112, 9.113
Probability cue	Either warning signal or presentation of a given S indicates a high probability of presentation of a particular S on the next trial	If the cued (high-probability) S occurs, RT is shorter than for the same S when there is no cueing; if a different (low-probability) S occurs, RT is longer than the same S when there is no cueing	CRef. 9.113

Factor	Description	Effect	References
Mapping	More than one S can be paired with (mapped onto) one R	Both the number of Ss and the number of Rs affect RT. For example, 2-2 (2S, 2R) mapping produces RT of 384 msec, 4-2 (4S, 2R) mapping produces RT of 500 msec, and 4-4 (4S, 4R) mapping produces RT of 572 msec	CRef. 9.111
	More than one R can be made to one S	More than one response possibility lengthens RT; degree of effect depends on response modality	Ref 1; CRef. 9.120
Compatibility	May be defined as population's preference for a given S-R pairing or may be a modality relationship that requires little translation from S to R	Highly compatible S-R pairing can abolish increased RT caused by additional alternatives or caused by decreased within-set probabilities	CRefs. 9.115, 9.116, 9.121
		Slope of function relating RT to number of alternatives or to probability is reduced	Ref. 1
		The effect of incompatibility is magnified when subject is unprepared or distracted by another task	
Stimulus Characteristics			
Similarity	Ss difficult to distinguish from each other	Increased stimulus similarity increases RT (e.g., shorter RT when 2 Ss are red and green than when they are red and orange)	Ref. 2
Set membership	Two digits such as 1 and 2 are more often considered a set than 2 and 7	For the unusual pair, RT is as long as if all the digits 1-9 are used	Ref. 1
Irrelevant information	Characteristics of a stimulus that, when considered alone, do not determine which response is to be made	Can usually be ignored. However, RT is much longer when the target S is made up of a combination of features, each of which appears in some of the other Ss	CRef. 9.117
Conflicting interpretation	When certain characteristics of S activate memories of conflicting interpretations	RT is lengthened	CRef. 9.118
Timing			
Warning signal	Time of foreperiod between warning signal and S	Optimal foreperiod of 200 msec speeds RT by 50-60 msec, but error rate increases at fastest RT (speed/accuracy tradeoff)	CRef. 9.114
Interstimulus interval	Can also be described as rate of presentation	When the interval between two Ss that demand Rs is shorter than the time to complete the first R, there is a delay in RT to the second S (psychological refractory period)	CRef. 9.107
Response-stimulus interval		RT is longer for shorter intervals	CRef. 9.113

9.111 Choice Reaction Time: Effect of Number of Alternatives

Table 1. Reaction time as a function of number of alternatives. (From Ref. 4)

Number of Alternative S-R pairs (N)	Reaction Time (msec)	Reaction Time Increment (msec)	RT Increment per Doubling of N (msec)
1	187	187	
2	316	129	1 to 2: 129
3	364	48	
4	434	70	2 to 4: 178
5	487	53	
6	532	45	3 to 6: 168
7	570	38	
8	603	33	4 to 8: 169
9	619	16	
10	622	3	5 to 10: 135

Key Terms

Choice reaction time; decision making; Hick-Hyman law; speed-accuracy tradeoffs

General Description

Reaction time (RT) increases as the number of stimuli and responses increases. Simple RT (Row 1 in the table), involving only one stimulus-response pair, is the shortest. The data in the second column of the table show that RT increases as the number of alternative stimulus-response pairs increases; the rate of increase is negatively accelerated (third column). As shown in the fourth column of the table, RT increases at a fairly constant rate as the number of alternatives (N) doubles; thus RT is a logarithmic function of the number of alternative stimulus-response pairs,

$$RT = a + b \log_2 N$$

where a and b are constants.

Methods

Test Conditions

- One to ten stimulus-response pairs (alternatives) used in each session and subjects knew set of alternatives before session
- Visually presented stimuli were Arabic numerals 1-5 and Roman numerals I-V
- Responses by fingers of right hand (in order) for Arabic numerals and left hand (in order) for Roman numerals, with each finger assigned to a specific response button

Experimental Procedure

- Independent variable: number of alternative stimulus-response pairs; session number for repeated sessions
- Dependent variable: RT for button press
- Subject's task: press appropriate response button as soon as stimulus was detected
- 10 subjects

Experimental Results

- RT increases as the number of alternative stimulus-response pairs increases, but the rate of increase is negatively accelerated.
- Applying the equation to the data yields $a = 173$ msec, which almost equals simple RT, and $b = 138$, which is the predicted increase in RT when the number of alternatives is doubled.
- Practice over 4 days (300 responses per condition) improves RT, but differences between conditions persist.

Variability

Individual differences were so great that data from one subject, who gave very fast inaccurate responses, are not included in the means in the table.

Repeatability/Comparison with Other Studies

Several studies have shown approximately the same pattern of RT when increasing from 1-10 alternatives.

Constraints

- The Hick-Hyman law of choice reaction time (RT) is $RT = a + bH_S = a + bH_T$, where H_S is the amount of information (number of bits) in the stimuli and H_T is the amount of information transmitted. Under ideal choice RT conditions in which an observer always responds with the single response associated with each stimulus, $H_S = H_T = \log_2 N$, where N equals the number of alternative stimulus-response pairs. However, this equality does not hold when conditions are not ideal. Then RT is more accurately a function of the amount of transmitted information, rather than the number of alternative stimulus-response pairs (Ref. 2).
- High stimulus-response compatibility can decrease effect of increasing alternatives (CRef. 9.116).

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• RT results depend on discriminability of alternatives; RT increases as alternatives become more similar.
• Mapping multiple stimuli to one response affects RT. For example, RT for four colors (or forms) mapped to two keys (500 msec) is shorter than RT for four colors (or forms) mapped to four keys (572 msec), but is longer than RT for two colors (or forms) mapped to two keys (384 msec).
• Choice RT is also affected by stimulus intensity, duration, and probability, as well as by many other factors (CRef. 9.108).

Key References

1. Kantowitz, B. H., & Sorkin, R. D. (1983). *Human factors: Understanding people-system relationships*. New York: Wiley.

2. Keele, S. W. (1970). Effects of input and output modes on decision time. *Journal of Experimental Psychology, 85*, 157-164.

*3. Keele, S. W. (1986). Motor control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes & performance*. New York: Wiley.

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Cross References

9.105 Speed-accuracy tradeoffs;

9.108 Factors affecting simple reaction time;

9.111 Reaction time: effect of uncertainty;

9.116 Choice reaction time: effect of stimulus-response compatibility

9.112 Choice Reaction Time: Effect of Probability of Alternatives

Table 1. Mean reaction time to nine stimuli (digits). (From Ref. 1)

Condition	Probability	RT (msec)		
Equal probability	0.11	390		
	High Probability	**RT (msec)**	**Low Probability**	**RT (msec)**
Unequal probability	0.24	375	0.095	405
	0.75	320	0.03	425
	0.94	285	0.01	440

In each unequal probability condition, the digit 1 was assigned a high probability; digits 2-9 were assigned equal and lower probabilities.

Key Terms

Choice reaction time; decision making, Hick-Hyman law; uncertainty

General Description

In a choice reaction time (RT) task, when the number of alternative stimulus-response pairs is increased, the probability of occurrence of any individual stimulus-response pair may decrease. When the alternative stimulus-response pairs (N) in a choice reaction time (RT) task are equally likely, RT can be predicted by

$$RT = a + b \log_2 1/p \quad (1)$$

where a and b are constants and $p = 1/N$, which is the probability of any particular alternative.

The effect of the number of alternatives can be separated from the effect of probabilities of individual alternatives by repeating one or more alternatives to create a set of alternatives with unequal probabilities. The RTs for equal-and unequal-probability conditions can then be compared as in the table. As the probability of a stimulus increases across conditions, the associated RT decreases. Conversely, when the probabilities of stimuli are decreased across conditions, the associated RTs increase. Thus there is a benefit to high-probability stimuli and a cost to low-probability stimuli when stimuli occur with unequal probabilities.

Equation 1 has been generalized to estimate mean RT across all events within a set of unequal probabilities. The RT to individual events must be weighted by the probabilities of the events, and the resulting equation is

$$RT = a + b \sum_{i=1}^{N} p_i \log_2 1/p_i \quad (2)$$

where N is the number of possible events and p_i is the probability of an individual event.

Methods

Test Conditions

- Alternatives were stimulus digits 1-9 paired with digit names as vocal responses
- Digits printed in 0.635-cm (1/4-in.) high black numerals on white cards and presented in 5.08 × 5.08-cm window at eye level in center of gray screen; stimulus duration and distance from subject not specified
- RT apparatus included throat microphone, electronic voice key, and clock with 0.01-sec accuracy
- Four probability conditions: p_1 - p_9 = 0.11, p_1 = 0.24 and p_2 - p_9 = 0.095 each, p_1 = 0.75 and p_2 - p_9 = 0.03 each, and p_1 = 0.94 and p_2 - p_9 = 0.01 each
- "Ready" signal 2 sec before shutter opened to present stimulus; subject told RT after each trial; interstimulus interval of ~10 sec
- Random order presentation of 126 stimuli per 1-hr session
- First session for each subject had equiprobable stimuli; to control for ability level, subjects were divided into sets of 12; each set of 12 divided into three groups of 4 subjects each, designated as high, medium, and low on the basis of RT for Digit 1 in the first session; members of each group of 4 randomly assigned to four probability conditions; subjects remained in assigned condition for Sessions 2-4

Experimental Procedure

- Independent variable: probability of alternatives
- Dependent variables: RT for vocal response, number of errors
- Subject's task: speak aloud name of presented digit
- 48 male college students

Experimental Results

- RT to the digit 1 is shorter than the RTs to the other digits by an average of 0.027 sec even when all stimuli are equally probable.
- The greater the probability of the most probable stimulus (Digit 1), the shorter its RT; conversely, the lower the probability of the other digits, the longer their RTs.
- The major changes in RTs occur in Session 2, (the first session with unequal stimulus probabilities); however, RT to the most probable stimulus (Digit 1) becomes shorter over sessions, while RTs to the less probable stimuli become longer over sessions.
- Overall mean RT decreases with practice.
- The overall error rate is relatively consistent for all sessions.
- For the condition with the greatest difference in probabilities, almost all errors consist of naming the most probable stimulus (Digit 1) when a less probable stimulus is presented; there is also a strong trend for this type of error in all conditions with unequally probable stimuli.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Variability

No mention of individual differences, but similar results were obtained in a replication where the same subjects served in all probability conditions.

Repeatability/Comparison with Other Studies

A similar pattern of results was found using the digit 5 as the most probable stimulus, after correcting for the consistently faster RT to the digit 1 (Ref. 1).

Constraints

- Motor responses to lights occurring with unequal probability yielded shorter RTs overall and less effect of differential probability than for the vocal responses used in this experiment.
- The Hick-Hyman law of choice reaction time (RT) is $RT = a + bH_S = a + bH_T$, where H_S is the amount of information (number of bits) in the stimuli and H_T is the amount of information transmitted. Under ideal choice RT conditions in which an observer always responds with the single response associated with each stimulus, $H_S = H_T = \log_2 N$, where N equals the number of alternative stimulus-response pairs. However, this equality does not hold when conditions are not ideal. The RT is more accurately a function of the amount of transmitted information, rather than the number of alternative stimulus-response pairs. For details on the computation of H_T in this type of situation, see Ref. 2.

Key References

*1. Fitts, P. M., Peterson, J. R., & Wolpe, G. (1963). Cognitive aspects of information processing: II. Adjustments to stimulus redundancy. *Journal of Experimental Psychology, 65*, 423-432.

2. Kantowitz, B. H., & Sorkin, R. D. (1983). *Human factors: Understanding people-system relationships*. New York: Wiley.

3. Keele, S. W. (1986). Motor control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive Processes and Performance*. New York: Wiley.

Cross References

9.106 Reaction time: effect of uncertainty;

9.111 Choice reaction time: effect of number of alternatives;

9.113 Choice reaction time: effect of stimulus probability and response-stimulus interval

9.113 Choice Reaction Time: Effect of Stimulus Probability and Response-Stimulus Interval

Key Terms

Choice reaction time; cueing; decision making; expectancy; Hick-Hyman law; speed-accuracy tradeoffs; uncertainty; warnings

General Description

In a choice reaction time (RT) task, correct information about which stimulus will occur next yields a benefit (a shorter RT than a control condition); when the information is incorrect, a cost is incurred (a longer RT than a control condition). Thus when a stimulus is a probabilistic predictor of which stimulus will be presented next, there is a benefit if a high-probability stimulus is presented and a cost if a low-probability stimulus occurs (Fig. 1). These benefits and costs are independent of the length of the response-stimulus interval (the interval between the end of the response to the predicting stimulus and the onset of the next stimulus).

A stimulus which is presented repeatedly (with no other intervening stimulus) generally yields a shorter RT, when all stimulus alternatives are equiprobable over an entire experimental session (Fig. 2a), and a highly probable repetitious stimulus (Fig. 2b) yields a shorter RT than a highly probable non-repetitious stimulus (Fig. 2c). However, if a non-repetitious stimulus is more probable than a repetitious stimulus, the RT to a repeated stimulus is similar to RT to other low-probability stimuli.

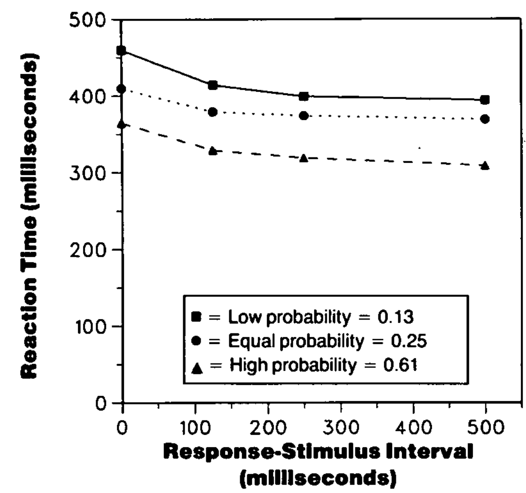

Figure 1. Mean reaction time as a function of response-stimulus interval (which is also the interstimulus interval) for low, equal, and high probability stimuli. (From *Handbook of perception and human performance*, based on Ref. 3)

Methods

Test Conditions

- Stimulus event was activation of one of four incandescent lamps mounted in a row, 2.54 cm (1 in.) apart center-to-center; each lamp covered with a white lens cap
- One response key located beneath each lamp; keys pressed by index or middle fingers of each hand, with one finger resting on each key throughout session
- Stimulus presented until correct key depressed and released, making response-stimulus intervals of 0, 125, 250, and 500 msec from release of key to onset of next stimulus equivalent to interstimulus interval
- Three conditions of sequential dependency: Equiprobable, with no constraints on the sequence of sequential light presentations; High-Probability Sequential, in which sequential light presentations followed one another in a partially predictable left-to-right order; High-Probability Repetition, similar to High-Probability Sequential, except that there was a high probability that one light would be activated repeatedly rather than changing to another light. Probabilities were: equiprobable ($p_{\text{all lights}} = 0.25$); High-Probability Sequential ($p_{\text{predicted}} = 0.61$ and $p_{\text{other lights}} = 0.13$ each); High-Probability Repetition ($p_{\text{repetition}} = 0.61$ and $p_{\text{other lights}} = 0.13$ each), predicted order of lights for sequential condition was light number 1, 2, 3, 4, 1
- Response-stimulus intervals blocked with 75 stimuli per block, eight blocks per session; one session on each of 3 days, with data from Day 1 discarded; subjects randomly assigned to conditions
- Feedback in the form of mean RT and number of errors for last 65 trials was displayed after each 75-trial block
- Not specified whether subjects were informed in advance about probability differences

Experimental Procedure

- Choice reaction time with four alternatives
- Independent variables: duration of response-stimulus interval, probability condition, event type (repetition, sequential, or neither); day of session
- Dependent variable: RT for key press
- Subject's task: depress key associated with lighted lamp
- 36 university students, some practice

Experimental Results

- The relative advantage arising from a highly probable stimulus is independent of the duration of response-stimulus interval, even when the response-stimulus interval is zero (Fig. 1).
- Repetitions of a stimulus generally yield shorter RTs when all stimuli are equiprobable (Fig. 2a) or when repetitions are more probable (Fig. 2b). However, if non-repetitious stimuli are more probable than repetitious stimuli, the RTs to repetitious stimuli are similar to the RTs to other low-probability stimuli.
- The function for repetitious events relating RT and duration of response-stimulus interval has a different shape than the corresponding functions for other event types.

Variability

Analysis of variance used to evaluate significance of results. No mean square errors were given.

Repeatability/Comparison with Other Studies

Results for the high-probability sequential condition (i.e., the sequence 1, 2, 3, 4, 1) were replicated on a new group of 8 subjects with the sequence 1, 3, 2, 4, 1. Also, RT is shorter for words, which have predictable letter sequences, than for random letters sequences (Refs. 1, 3; CRef. 9.303).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- RT would not be independent of the interstimulus interval if the response were made during the interstimulus interval (CRef. 9.107).
- Blocks with more than five errors were rerun at the end of each session, but neither number of errors, number of blocks rerun, nor the number of errors for the repeated blocks is specified, so the benefits and costs resulting from the probability cue cannot be considered in terms of a speed-accuracy tradeoff.
- The Hick-Hyman law of choice reaction time (RT) is $RT = a + bH_S = a + bH_T$, where H_S is the amount of information (number of bits) in the stimuli and H_T is the amount of information transmitted. Under ideal choice RT conditions in which an observer always responds with the single response that is associated with each stimulus, $H_S = H_T = \log_2 N$, where N equals the number of alternative stimulus-response pairs. However, this equality does not hold when conditions are not ideal. Then RT is more accurately a function of the amount of transmitted information, rather than the number of alternative stimulus-response pairs. For details on the computation of H_T in this type of situation see Ref. 2.

Key References

1. Hershman, R. L., & Hillix, W. A. (1965). Data processing in typing: Typing rate as a function of kind of material and amount exposed. *Human Factors, 7*, 483-492.

2. Kantowitz, B. H., & Sorkin, R. D. (1983). *Human factors: Understanding people-system relationships*. New York: Wiley.

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4. Shaffer, L. H., & Hardwick, J. (1968). Typing performance as a function of text. *Quarterly Journal of Experimental Psychology, 20*, 360-369.

Cross References

9.102 Reaction time: effect of uncertainty;

9.105 Speed-accuracy tradeoffs;

9.107 Serial reaction time: effect of signal spacing;

9.303 Typing speed and accuracy;

Handbook of perception and human performance, Ch. 30, Sect. 1.2

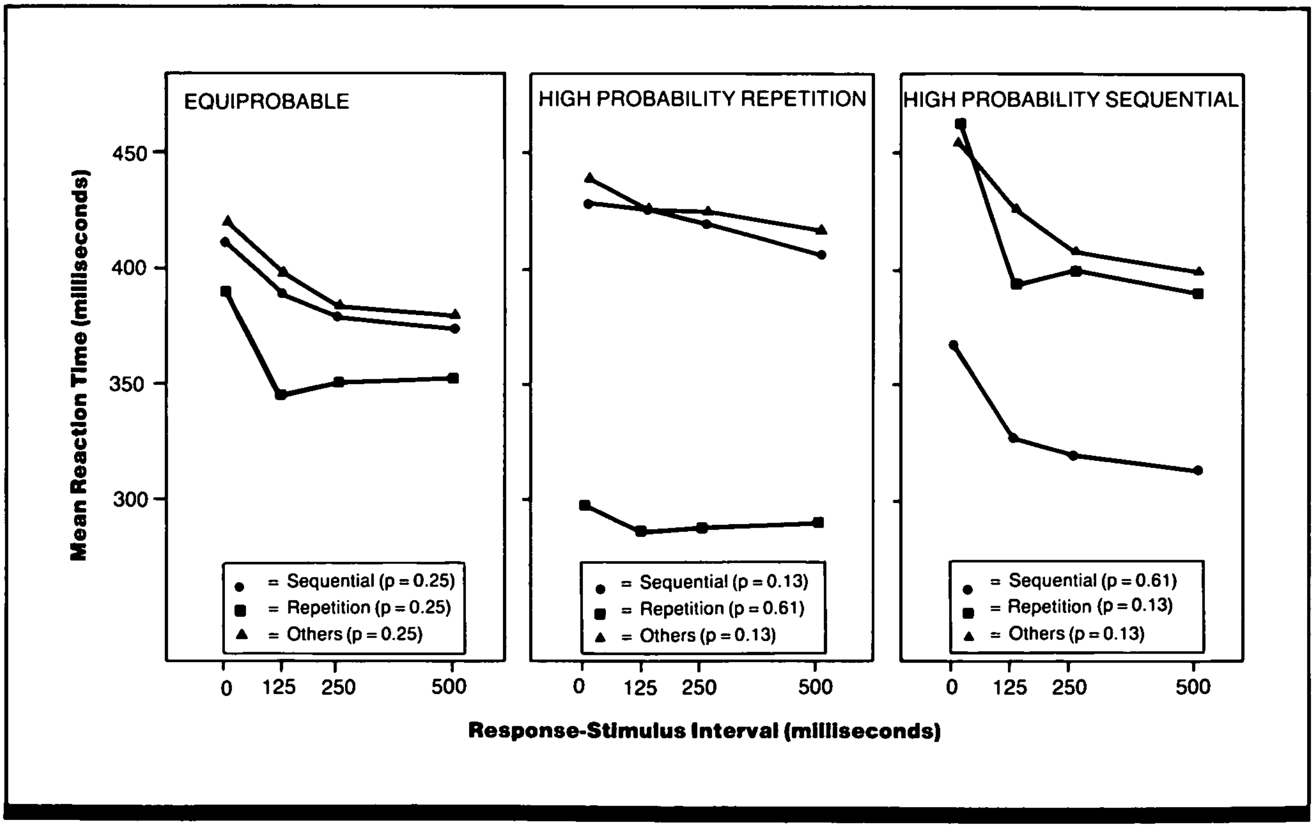

Figure 2. Mean reaction time as a function of response-stimulus (interstimulus) interval for three event types (sequential, repetitious, and other) for each of three probability conditions (equiprobable, highly probable repetitious, and highly probable sequential). (From Ref. 3)

9.114 Choice Reaction Time: Effect of Warning Interval on Error

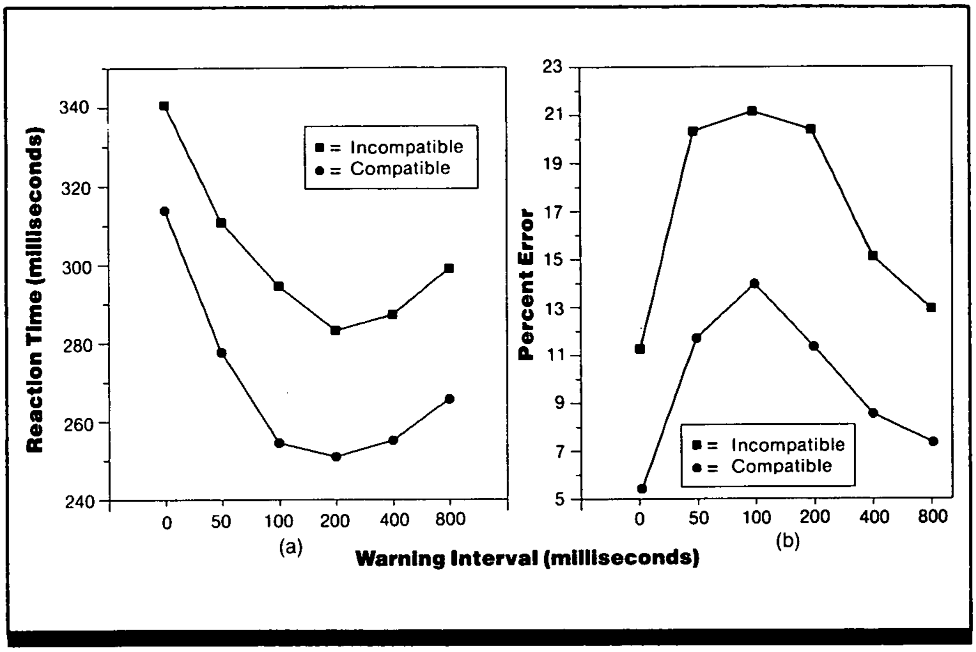

Figure 1. Functions relating (a) RT for correct responses and (b) errors to duration of warning-signal interval for compatible and incompatible pairings of stimuli and responses (Study 1). (From Ref. 2)

Key Terms

Choice reaction time; expectancy; human error; speed-accuracy tradeoffs; stimulus-response compatibility; warnings

General Description

The function relating reaction time (RT) to warning interval is U-shaped, with the shortest RT occurring when the interval is 200 msec. On the other hand, the function relating percent error to warning interval is an inverted U with the greatest percentage of errors at 100 msec. This relation in which RT decreases and error rate increases is known as speed-accuracy tradeoff. A compatible stimulus and response (e.g., right response to right stimulus) yield shorter overall RT and fewer errors than an incompatible stimulus and response (e.g., right response to left stimulus). When a warning signal also serves as a prime (gives some information about the upcoming stimulus), RT decreases compared to a noninformative warning, reaching a maximum at ~200 msec after the warning signal's onset. For an interval <200 msec between a non-prime warning signal onset and stimulus presentation, there is almost no cost (i.e., no increase in RT compared to a control condition); cost later accrues and almost reaches maximum at ~300 msec.

Methods

Test Conditions

Study 1 (Ref. 2)

- 50-msec warning tone (not described) followed by presentation of an X (the stimulus) on left or right of a centered vertical line on oscilloscope
- For compatible condition, stimulus and response key on same side (left-left, right-right); for incompatible condition, stimulus and response key on opposite sides (left-right, right-left)
- Intervals from offset of warning tone to onset of X varied from 0-800 msec, with 0 value indicating no warning tone occurred; intertrial intervals varied from 2-5 sec
- RT and error feedback displayed on oscilloscope after each trial
- Instructions to subject stressed speed and not accuracy

Study 2 (Ref. 3)

- Stimuli were two capital letters to be judged as same (e.g., AA) or different (e.g., AB)
- Two response keys, one to indicate same judgments and one to indicate different judgments
- Two types of warning signals: a plus sign (neutral) and a capital letter (valid or invalid prime); each type of warning signal occurred on 50% of the same-judgment trials and 50% of the different-judgment trials; the capital letter also served as a valid prime on 80% of the same-judgment trials (i.e., the capital letter presented as a warning signal matched the stimulus letter pair for the same-different judgment) and an invalid prime on the other 20%
- Interval between warning signal and stimulus presentation was either 10, 50, 150, 300, or 500 msec

Experimental Procedure

Study 1

- Two-alternative RT task
- Independent variables: stimulus-response pairing, interval between warning signal onset and stimulus presentation
- Dependent variables: RT for correct responses and percent errors
- Subject's task: press appropriate key for same or different judgment RT
- 9 university students, some practice

Study 2

- Independent variables: warning signal, interval between warning signal onset and stimulus presentation
- Dependent variable: RT
- Subject's task: detect pair of capital letters and press appropriate key for same/different judgment
- 12 subjects

Experimental Results

Study 1

- RT for correct responses ($p < 0.01$) and percent errors ($p < 0.1$) varies with warning-signal interval.
- There is a clear but imperfect inverse relation (a speed-accuracy tradeoff) between RT for correct responses and errors across warning-signal intervals. The U-shaped RT functions reach minima at 200 msec for both compatibility conditions (Fig. 1a); the inverted U-shaped error functions reach maxima at 100 msec for both compatibility conditions (Fig. 1b).
- Compatible stimulus-response pairing yields shorter RTs for correct responses ($p < 0.1$) and fewer errors ($p < 0.01$) than incompatible stimulus-response pairing.
- Without a warning signal (an interval of zero), incorrect responses are made as quickly as correct responses; with a warning signal, RTs for errors are shorter than RTs for correct responses.

Study 2

- Benefits, the amount by which the cue improved RT compared to the neutral warning, are calculated by subtracting the RT for same judgments made after a valid prime warning signal from the RT for same judgments following a neutral warning signal; costs (degree of response inhibition) are obtained by subtracting the RT for same judgments made after an invalid prime from the same control (neutral) RTs.

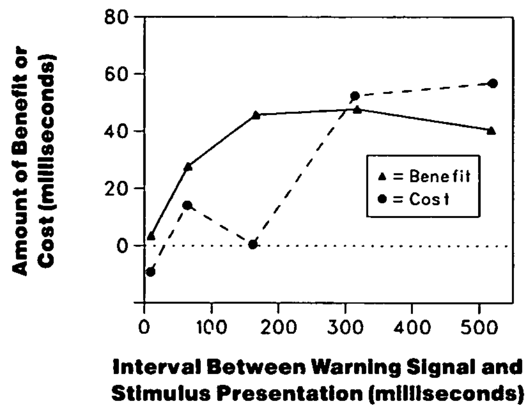

Figure 2. Benefit (decrease in RT) and cost (increase in RT), relative to a neutral warning signal for a primed stimulus as a function of length of interval between warning signal onset and stimulus presentation (Study 2). (From Ref. 3)

- Benefits reach a maximum by 150 msec with significant facilitation at all stimulus-onset intervals.
- Costs are significant only at 300 and 500 msec.

Variability

No information on variability was given; all subjects served in all conditions.

Repeatability/Comparison with Other Studies

These results fit into a detailed analysis of the processes facilitating RT (Ref. 1). A 500-msec interval yielded optimal performance for two processes for three different tasks requiring same-different judgments.

Constraints

- Comparing absolute RT values for experiments using a warning signal such as a tone (Study 1) with experiments using a visual signal that may serve both as a warning signal and a prime for the following stimulus (Study 2) may confound issues of timing, probability cueing, priming, and modalities.
- In Study 1 the stimulus was presented until a response was made; a very different function relating RT and errors could be expected if the stimulus were presented for a specified, brief duration.

Key References

1. Posner, M. I., & Boies, S. J. (1971). Components of attention. *Psychological Review, 78,* 391-408.

*2. Posner, M. I., Klein, R., Summers, J., & Buggie, S. (1973). On the selection of signals. *Memory and Cognition, 1,* 2-12.

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Cross References

9.105 Speed-accuracy tradeoffs;

9.112 Choice reaction time: effect of probability of alternatives;

9.113 Choice reaction time: effect of stimulus probability and response-stimulus interval;

Handbook of perception and human performance, Ch. 30, Sect. 1.2

9.115 Choice Reaction Time: Effect of Stimulus-Response Compatibility on Error

Key Terms

Choice reaction time; human error; stimulus-response compatibility

General Description

Stimulus-response compatibility can be defined as the degree to which a given pairing of a stimulus and response is the pairing preferred by a majority of people doing the task (sometimes referred to as population stereotypes). Highly compatible pairings of stimuli and responses (e.g., making a movement to the right when the stimulus is on the right) yield shorter reaction times (RT) and fewer errors than incompatible stimulus-response pairings (e.g., making a movement to the left when the stimulus is on the right). Compatibility of the stimulus-response pairs can be a more important determinant of performance than either the form of the stimuli or the form of the responses.

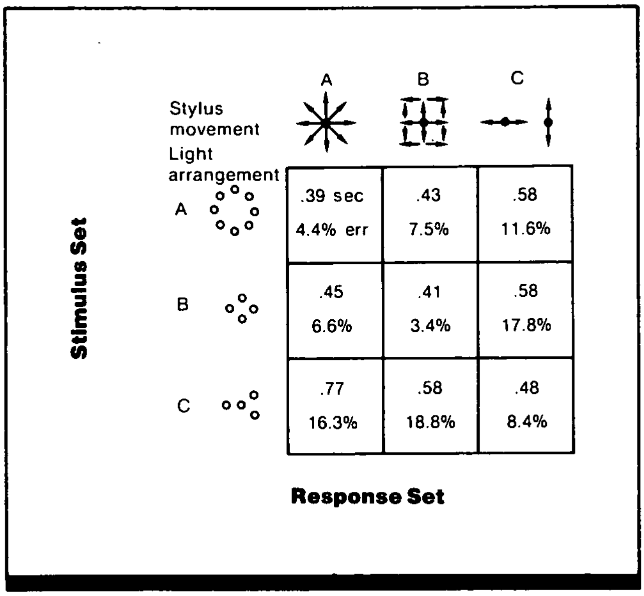

Figure 1. Reaction time and percent errors for pairing of each of three stimulus arrays with each of three response patterns. (From *Handbook of perception and human performance*, adapted from Ref. 1)

Methods

Test Conditions

- Subjects seated in front of stimulus panels mounted at 60-deg angle to the horizontal, 15 deg downward, and 71.12 cm (28 in.) from subject's eyes; response panels mounted 30 deg to the horizontal at unspecified distance from subject
- The stimulus-response relationships are illustrated in Fig. 1. An *A* stimulus was the onset of one of eight equally spaced lights forming a circle; an *A* response was a hand movement along one of eight paths radiating from a central point like spokes of a wheel; a *B* stimulus was onset of either one of four lights separated by 90 deg or one of four two-combinations formed by adjacent pairs; *B* responses were either single horizontal or single vertical hand movements or both a horizontal and a vertical hand movement to reach a corner; a *C* stimulus was onset of either one of a pair of horizontally separated lights, one of a pair of vertically separated lights, or one horizontal light and one vertical light; a *C* response was a left or right movement of the left hand, an up or down movement of the right hand, or one of the four possible combinations using both hands
- When experimenter said "Center," subject placed stylus (or styli for *C*) on a 0.3176-cm (1/8 in.) diameter metal disc at the center of each set of response paths; experimenter then said "Ready" a few seconds before the stimulus presentation
- Forty stimulus presentations per subject; order of presentations randomized; equal frequencies of all eight stimuli

Experimental Procedure

- Independent variable: stimulus-response compatibility (each of three sets of stimuli paired with each of three sets of responses)
- Dependent variables: RT, measured from stimulus onset until the stylus left the metal disc; for two-handed responses, RT was the mean RT of the two responses; percentage of errors
- Subject's task: detect single onset of stimulus and move stylus along path to terminal position corresponding to stimulus
- 72 right-handed airmen (ages 18-29) with some practice; two-choice RT scores for 153 right-handed men used to form eight groups of 9 subjects each with homogeneous within-group mean RT; experimental group for each stimulus-response pair condition formed by randomly drawing one subject from each of eight groups

Experimental Results

- For each stimulus array, the most physically similar response pairings (*A-A*, *B-B*, and *C-C*) yield the shortest RT and fewest errors (the values on the diagonal in the figure).
- The RTs for the *A-A* and *B-B* stimulus-response pairs (which use only one hand) are not significantly different from one another and are shorter than the pairings of *C* stimuli and *C* responses (which include one- and two-handed responses).
- Responses made with only the right hand in the *C-C* condition (RT = 0.41 sec) are comparable to *A-A* and *B-B* responses and are faster than responses made with only the left hand in the *C-C* condition; for *C* responses using two hands, the hands do not differ in RT.
- There are significant differences among the RTs for the stimulus arrays when the RTs for the three response sets are averaged ($p<0.01$) and among the RTs for the response sets when RTs are averaged for the three stimulus arrays ($p<0.01$).
- In general, the rankings of the conditions for error data agree with the rankings of the conditions for RT data.

Variability

The pairings of stimuli and responses (the interaction term in the analysis of variance) contribute more to the variance than either differences among stimulus arrays or differences among response sets considered alone. There was no significant departure from homogeneity of variance among subjects.

Repeatability/Comparison with Other Studies

Thirty-two sessions were run over a 2 1/2-month period with 5 subjects. The RTs for *A* stimuli were the shortest; the RTs for *C* stimuli were always the longest (Ref. 1). References 2 and 3 investigated the effects of varying both stimulus and response sets.

Constraints

- Two-handed responses do not seem comparable to one-handed responses.
- What constitutes the compatibility is never analyzed, but is based on population stereotypes.

Key References

*1. Fitts, P. M., & Seeger, C. M. (1953). S-R compatibility: Spatial characteristics of stimulus and response codes. *Journal of Experimental Psychology, 46*, 199-210.

2. Knowles, W. B., Garvey, W. D., & Newlin, E. P. (1953). The effect of "speed" and "load" on display-control relationships. *Journal of Experimental Psychology, 46*, 65-76.

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Cross References

9.111 Choice reaction time: effect of number of alternatives;

9.112 Choice reaction time: effect of probability of alternatives;

9.113 Choice reaction time: effect of stimulus probability on response-stimulus interval;

9.114 Choice reaction time: effect of warning interval on error;

Handbook of perception and human performance, Ch. 30, Sect. 1.2

9.116 Choice Reaction Time: Effect of Stimulus-Response Compatibility

Table 1. Mean reaction time (milliseconds) and proportion of errors to high- and low-frequency stimuli associated with high- and low-frequency responses. (From Ref. 3)

		High Compatibility	Low Compatibility: Common Name	Low Compatibility: Different Name
High-frequency stimulus with high-frequency response	RT Error	573 0.005	689 0.009	755 0.017
Low-frequency stimulus with high-frequency response	RT Errors	607 0.016	771 0.066	979 0.078
Low-frequency stimulus with low-frequency response	RT Errors	614 0.019	905 0.172	1272 0.246

Key Terms

Choice reaction time; expectancy; response probability; speed-accuracy tradeoffs; stimulus-response compatibility

General Description

When considered separately, increasing stimulus and/or response probabilities (i.e., relative frequencies) decreases choice task reaction time (RT), as does increasing the degree of compatibility of stimulus-response pairings (i.e., the degree to which a pair of stimuli and responses is that preferred by a majority of subjects doing the task). When considered together, the size of the probability effect depends on the degree of compatibility. When stimuli and responses are highly compatible, the RTs for high- and low-probability stimuli do not significantly differ (irrespective of response); when the stimulus-response pairings are incompatible, there are large decreases in RTs of correct responses with increases in stimulus probability or response probability.

Methods

Test Conditions

- Visual stimuli were three uppercase (D, Q, and H) and six lowercase letters (d, q, h, k, b, and p) presented tachistoscopically for 1 sec on a white background 43.18 cm from subject
- Six letters used for each of three compatibility conditions, with one letter having a probability of 0.50 and all other letters having probabilities of 0.10; all letters but H and h (which served as distractors) served as the high-probability letter for some subjects
- Responses were names of letters with capitalization irrelevant (e.g., D indicates "dee" as response); stimuli to response mapping was 2:1 for each compatibility condition; for high compatibility, two stimuli shared a common name that was the response (i.e., D, d with D as response, Q, q with Q, and H, h with H); for low compatibility, common-name, two stimuli shared a common name and a response that was the name of a different letter (i.e., D, d with Z, Q, q with V, and H, h with J); for low compatibility, different-name, two stimuli with different names shared a response of the name of different letter (i.e., D, k with Z, Q, b with V, and H, p with J)
- For each compatibility condition, the response for stimulus pair containing the high-probability letter had a probability of 0.60 and all other responses had a probability of 0.20
- 1-sec warning tone immediately before onset of stimulus; intertrial interval of 3.5 sec
- Index card showing stimuli and associated probabilities and responses was constantly available to subject

Experimental Procedure

- Six-alternative choice RT task; one session of 240 stimulus presentations lasting ~1 hr per subject; sessions analyzed as four 60-trial blocks
- Independent variables: stimulus probability, response probability, stimulus-response compatibility condition
- Dependent variable: RT of correct responses
- Subject's task: speak aloud response (one of three) to stimulus (one of six); subject informed of RT after correct response and notified of error after incorrect response
- 14 male and 10 female subjects, all college students with normal or corrected vision; a practice two-choice RT task used to designate 12 slow responders and 12 fast responders; one-third of each type randomly assigned to one of the three compatibility conditions

Experimental Results

- The RTs of correct responses for low-probability stimuli with low probability responses for compatible stimulus-response pairings are much shorter than the correct RTs for high-probability stimuli with high probability responses for incompatible stimulus-response pairings.
- A high-probability response to a low-probability stimulus is significantly faster than a low-probability response for incompatible stimulus-response pairings, but not for compatible pairings.
- Increasing response probability decreases RTs of correct responses more for the low-compatibility, different-name condition than for the low-compatibility, common-name condition, but the magnitude of the difference between conditions declines with practice.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Variability

Only RTs of correct responses were input into the analysis of variance; no mean square errors were reported.

Repeatability/Comparison with Other Studies

The effect of stimulus probability on RT has been found in several studies (CRefs. 9.111, 9.112, 9.113) as has the effect of the degree of compatibility of stimulus-response pairings (CRefs. 9.114, 9.115). Although there is an effect of response probability (Ref. 1), its causes and the degree of the effect are not clear.

Constraints

- Although there is supposedly a 2:1 mapping in the high-compatibility and low-compatibility, common-name conditions, it could be argued that using upper and lower cases of the same letter is not the same 2:1 mapping as in the low-compatibility, different-name condition.
- The Hick-Hyman law of choice reaction time (RT) is $RT = a + bH_S = a + bH_T$, where H_S is the amount of information (number of bits) in the stimuli and H_T is the amount of information transmitted. Under ideal choice RT conditions in which an observer always responds with the single response associated with each stimulus, $H_S = H_T = \log_2 N$, where N equals the number of alternative stimulus-response pairs. However, this equality does not hold when conditions are not ideal. Then RT is more accurately a function of the amount of transmitted information, rather than the number of alternative stimulus-response pairs. For details on the computation of H_T in this type of situation, see Ref. 4.

Key References

1. Greenwald, A. G. (1970). A double stimulation test of ideometer theory with implications for selective attention. *Journal of Experimental Psychology, 84*, 392-398.

2. Hawkins, H. L., MacKay, S. L., Holley, S. L., Friedin, B. D., & Cohen, S. L. (1973). Locus of the relative frequency effect in choice reaction time. *Journal of Experimental Psychology, 101*, 90-99.

*3. Hawkins, H. L., Snippel, K., Presson, J. C., MacKay, S., & Todd, D. (1974). Retrieval bias and the response relative frequency effect in choice reaction time. *Journal of Experimental Psychology, 102*, 910-912.

4. Kantowitz, B. H., & Sorkin, R. D. (1983). *Human factors: Understanding people-system relationships*. New York: Wiley.

Cross References

9.101 Reaction time tasks and variability;

9.105 Speed-accuracy tradeoffs;

9.108 Factors affecting simple reaction time;

9.111 Choice reaction time: effect of number of alternatives;

9.112 Choice reaction time: effect of probability of alternatives;

9.113 Choice reaction time: effect of stimulus probability and response-stimulus interval;

9.114 Choice reaction time: effect of warning interval on error;

9.115 Choice reaction time: effect of stimulus-response compatibility on error

9.117 Choice Reaction Time: Detection of Targets Amid Irrelevant Stimuli

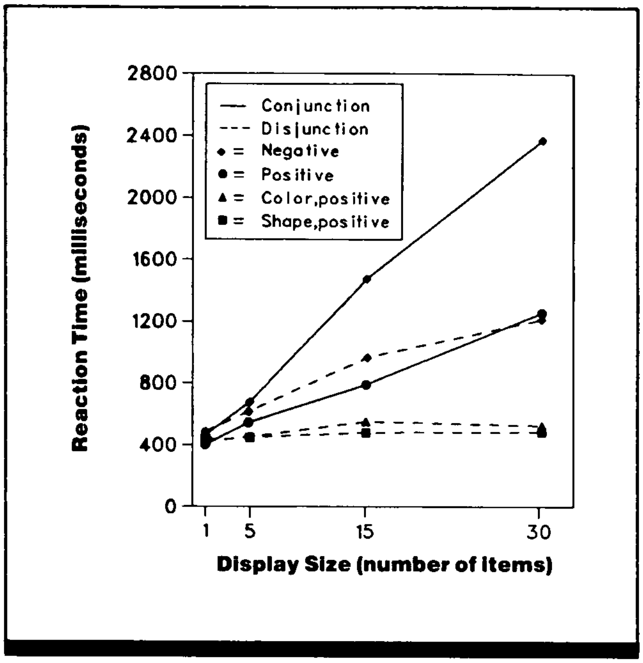

Figure 1. Reaction times for positive and negative responses for detecting targets amid displays of irrelevant information (distractor items) as a function of the number of items in the displays (Exp. 1). Targets were of two types, those with a unique feature (disjunction condition) and those which features shared with the distractors (conjunction condition). (From Ref. 2)

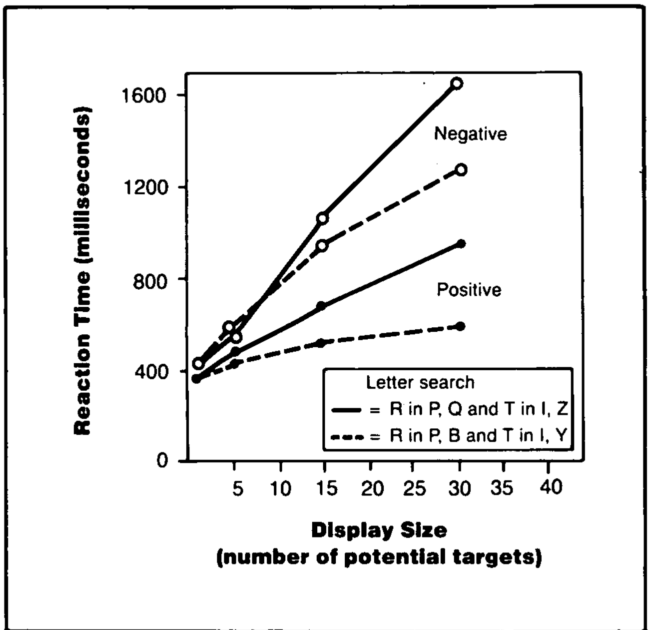

Figure 2. Reaction times for positive and negative responses for detecting targets defined by a unique feature (e.g., the diagonal line of R in a display of Ps and Bs) or by conjunction amid distractors (Exp. 2). (From Ref. 2)

Key Terms

Alerting systems; attention cueing; choice reaction time; distractors; exhaustive search; parallel search; self-terminating search; serial search; signal detection; target acquisition; visual search; warnings

General Description

In a choice reaction time (RT) task requiring detection of a target amid a field of distractors (e.g., an array of irrelevant letters), the subject indicates whether the target is present (positive trials) or absent (negative trials). If the target has a unique single feature that is not possessed by any of the distractors, RT is short even if the target and distractors have other features in common. Also, increasing the number of distractors does not affect RT, suggesting that the items are processed in parallel (i.e., all items are processed simultaneously).

When the target shares one feature with half the distractors and another feature with the other half, subjects must look for a conjunction of the two features to locate the target. In this case, RT is longer and increases linearly with the addition of distractors. Also, the slope of the function relating RT to the number of distractors for positive responses is about half the slope of the corresponding function for negative responses. This indicates that a serial search (an item-by-item process) occurs. For the positive conditions, the search terminates as soon as the target is located; for the negative condition, an exhaustive search is carried out and all items are processed.

Methods

Test Conditions

- Tachistoscopic presentation of stenciled letters on white cards; displays of 1, 5, 15, or 30 letters per card; each letter subtended 0.8 x 0.6 deg of visual angle and each display subtended 14 x 8 deg
- Experiment 1 used colored letters with single feature condition defined as shape (letter S) or color (blue); single feature targets were green S, brown S, blue X, or blue T in a field of brown Ts and green Xs; conjunction-condition target was a green T in a similar field
- Experiment 2 used black letters; single feature condition was either an R target in a field of Ps and Bs or a T target in a field of Is and Ys; the conjunction-condition target was either an R target in a field of Ps and Qs or a T target in a field of Is and Zs
- White card displayed "Ready" signal, then 1-sec display of white card with central fixation spot, then stimulus card displayed

Experimental Procedure

- Visual-search paradigm
- Independent variables: target of

C-3

either single feature or conjunction of features, number of items in display
• Dependent variable: RT for key press (index finger of dominant hand for positive responses and non-dominant hand for negative responses); error trials were repeated in the same session and a dummy trial, presented after each error trial, was dropped from the data; RT and error feedback given
• Subject's task: detect target amid distractors and respond by key press to indicate presence or absence of target
• In Exp. 2, subjects were instructed to consistently use search strategy for a unique (i.e., disjunctive) feature when possible
• 6 subjects in each experiment (members of the Oxford subject panel, ages 24-29); in Exp. 1 three of the six subjects had participated in a previous search experiment; in Exp. 2, of the six participants in the conjunction and similarity conditions, four had participated in one previous research experiment for colored letters.

Experimental Results

Experiment 1

• For both positive and negative responses in the conjunction condition, the scanning rate is ~60 msec per item and search time has an almost perfect linear increase with number of items displayed; the slope for negative responses is just over double that of positive responses. Therefore search appears to be serial and self-terminating.

• For positive responses in the single-feature condition, search time is relatively unaffected by number of times displayed; for negative responses, there is a highly linear increase in search time as display size increases; the slope ratio for positive to negative responses is 1:8. Therefore detection of targets is by means of parallel processing and the entire display is scanned if no target is immediately detected.

Experiment 2

• The ratio of the slopes for positive and negative responses is similar to that of Exp. 1, indicating a serial and self-terminating search. The ratio for the feature condition is much lower (1:4) as in Exp. 1, again indicating that different search processes are used for positive and negative responses.

• Search time increases linearly with increasing number of items displayed for both positive and negative responses in the conjunction condition and for negative responses in the feature condition. However, the slope for the positive responses in the conjunction condition is less than the slope for the negative responses for the feature condition, so the effect of number of items displayed on positive responses, which is unexpected, is smaller.

Variability

All subjects in Exp. 1 had the same pattern of results and varied only in absolute values of slopes and intercepts. No information on variability is given for Exp. 2.

Repeatability/Comparison with Other Studies

The two experiments described here are part of a larger series that replicates the results under several different conditions (Ref. 2). However, some research (Ref. 1) has demonstrated that increases in the number of distractors do not affect RT when there are categorical differences between the target and the distractors, even when shared features would lead to an expectation of increases in RT.

Constraints

• Positive responses were always made with the dominant hand and negative responses were always with the non-dominant hand.

• These results may be influenced by amount of practice. The slope of the RT fixation for conjunctive items will decrease with practice if the same subset of stimuli are targets across trials (consistent mapping).

Key References

1. Egeth, H., Jonides, J., & Wall, S. (1972). Parallel processing of multielement displays. *Cognitive Psychology, 3*, 674-698.

*2. Treisman, A. M., & Gelade, G. (1980). A feature integration theory of attention. *Cognitive Psychology, 12*, 97-136.

Cross References

7.219 Division of attention among spatial locations;

7.221 Attentional and decision-making factors in component and compound tasks;

7.405 Application of signal detection theory (SDT) to vigilance;

7.515 Processing of nontarget items in visual search;

7.516 Target acquisition in distractor target arrays;

7.613 Effect of alerted and unaltered search on target acquisition;

9.111 Choice reaction time: effect of number of alternatives;

9.112 Choice reaction time: effect of probability of alternatives;

9.118 Choice reaction time in the presence of conflicting information;

Handbook of perception and human performance, Ch. 30, Sect. 3.4

9.118 Choice Reaction Time in the Presence of Conflicting Information

Key Terms

Attention cueing; choice reaction time; distractors; signal detection; stimulus-response compatibility; Stroop effect; target acquisition; visual search

General Description

Information in a stimulus specified as irrelevant to a choice reaction time (RT) task may activate information stored in memory. If the activated information supports a decision that conflicts with the relevant dimension of the task, interference may lead to an increased number of errors and/or to longer RTs. The classic paradigm is the Stroop task: a color word like "blue" is printed in red ink; the task is to name the color of the ink, and the printed word (the color name) is the irrelevant information. This results in longer response times. If, however, the task is to name the word, and the color of the ink in which it is printed is the irrelevant portion of the stimulus, no such interference occurs. The table describes several variations on the Stroop task that attempt to locate the source of the interference, gives the results, describes a similar conflict found with auditory stimuli, and lists many other situations where interference effects have resulted in longer RTs.

Table 1. Summary of studies of reaction time in the presence of conflicting information.

Task	Results	Source
Name ink color of stimulus; stimulus was a row of x's (neutral control), a congruent object ("grass" in green ink), an incongruent object ("grass" in red ink), or color name (congruent or incongruent)	Both incongruent object names and incongruent color names interfere with naming ink color (i.e., RT is longer than for the control condition); a highly congruent object (e.g., "grass" in green) also increases RT. Therefore, the effect carries across semantic associations	Ref. 1
Name color of ink patch on one side of fixation point; patch alone (control) or color name printed in black ink on opposite side of fixation point	Interference by incongruent color name occurs even when there is spatial separation between the color name and the color patch	Ref. 2
Push one of four keys to indicate stimulus color (one color associated with each key); color patch only, neutral irrelevant word, or incongruent color name	Incongruent color names lengthen RT, but unrelated words do not affect RT	Ref. 4
Press key on right to high tone and key on left to low tone; irrelevant aspect of stimulus was ear of tone presentation	There is interference (RT is lengthened) when the tone occurs in the ear opposite the hand used to respond (Fig. 1). There is still a delay after extensive responding (during the fifth experimental session)	Ref. 5
Other types of tasks that involve processing conflicting information: (1) between the direction an arrow is pointing and the arrow's position in space; (2) between words like: "up," "down," "above," "below," "left," "right," "north," "south," "east," "west," and the position of the word in space; (3) for same/different judgments about the size of type in which words are printed when the two words printed are the same word or different words; (4) between the number of digits and the numerical value of the digits (e.g., tell the number of digits displayed while seeing three number 4's); and (5) between the size of pictured objects and their real size (e.g., name the larger pictured animal while seeing a large mouse and a tiny elephant	RT is slower whenever conflicting information is presented	Ref. 3

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Except for the auditory task, most of the tasks listed here involve either the reading of words, the production of words, or the assignment of words to keys. With children and adults who can read, but for whom reading has not become an effortless (automatic) process, the Stroop effect does not occur.

Key References

1. Dalrymple-Alford, E. C. (1972). Associative facilitation and interference in the Stroop color-word task. *Perception & Psychophysics, 11*, 274-276.

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Cross References

7.219 Division of attention among spatial locations;

7.221 Attentional and decision-making factors in component and compound tasks;

7.405 Application of signal detection theory (SDT) to vigilance;

7.515 Processing of nontarget items in visual search;

7.516 Target acquisition in distractor target arrays;

9.111 Choice reaction time: effect of number of alternatives;

9.112 Choice reaction time: effect of probability of alternatives;

9.116 Choice reaction time: effect of stimulus-response compatibility;

9.117 Choice reaction time: detection of targets amid irrelevant stimuli

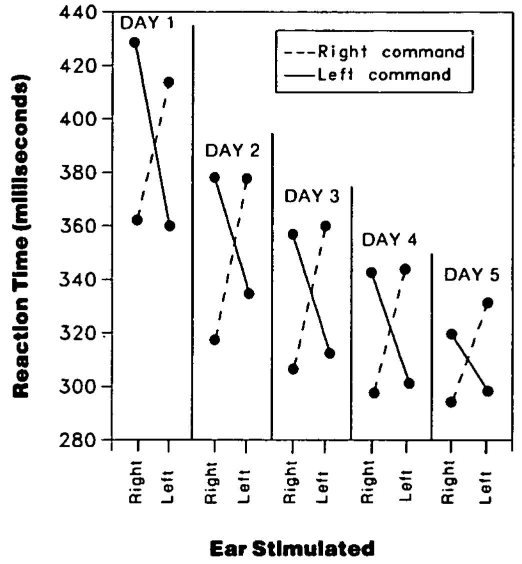

Figure 1. Key press reaction time to tones requiring a left or right response as a function of ear of occurrence and amount of practice. (From Ref. 5)

9.119 Choice Reaction Time: Effects of Practice

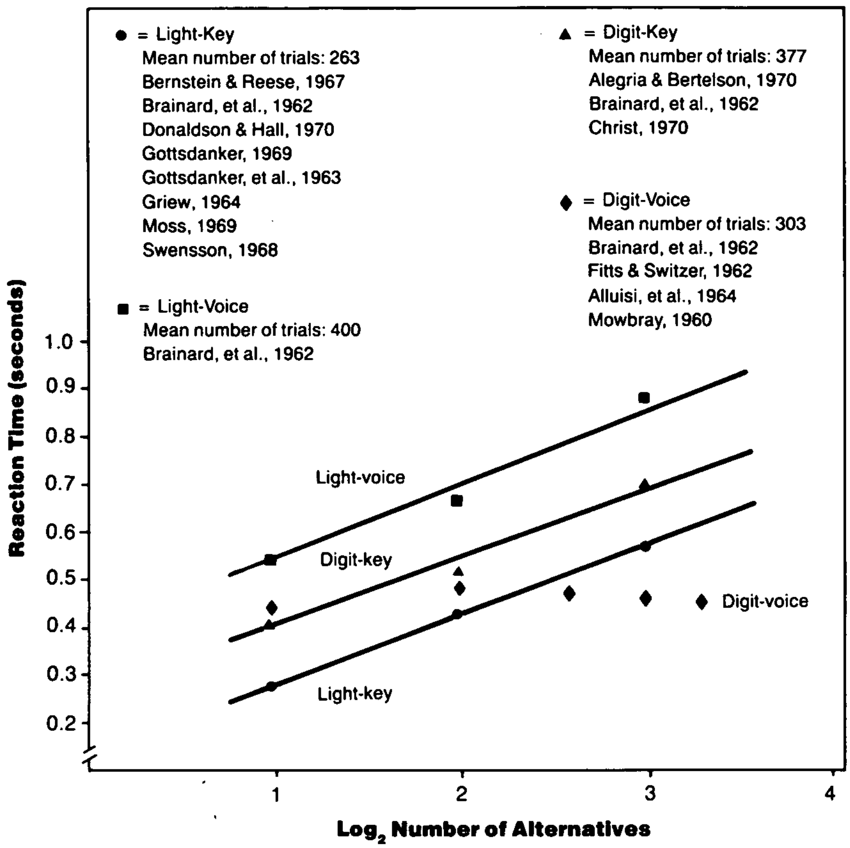

Figure 1. Choice RT as a function of number of alternatives at low practice levels. See Ref. 2 for full citations of reviewed studies. (From Ref. 2)

Key Terms

Choice reaction time; expectancy; Hick-Hyman law; practice; stimulus-response compatibility; visual reaction time

General Description

When visual stimuli are presented as alternatives in choice reaction time (RT) tasks, the number of alternatives and the compatibility of the stimuli and response modes affect RT (CRefs. 9.111, 9.112). A large number of alternatives increase RT, and stimulus-response (S-R) compatibility decreases RT; the compatibility effect can abolish the effect of number of alternatives (Fig. 1).

Practice on RT always decreases RT; however, number of alternatives and S-R compatibility interact with practice. That is, RT decreases the most with great incompatibility and a large number of alternatives.

Methods (across studies)

(59 visual choice RT studies)

1. Digits or lights as visual stimuli
2. Key press or vocalization as response mode
3. RT measured from stimulus onset to initiation of response (or corrected for movement time)
4. RT for incorrect responses excluded
5. Subjects were normal young adults
6. Central binocular vision employed
7. Parameters varied: number of alternatives (N_A): 2-8 [expressed as 1-4 bits ($\log_2 N_A$)]; amount of practice, i.e. number of trials (N_T): 64-63,000

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Figure 1 shows that with relatively low levels of practice, the means of choice RT:
  1. are lowest for $N_A \leq 4$ light-key combinations ($\log_2 N_A = 2, 2^2 = 4$)
  2. are lowest for $N_A \geq 5$ digit-voice combinations ($\log_2 N_A = 2.3, 2^{2.3} = 5$)
  3. are independent of N_A for digit-voice combinations
  4. are directly proportional to $\log_2 N_A$ for other combinations
  5. for light-key, digit-key and light-voice combinations, $RT = \log_2 N_A + B$, with slope nearly the same for all combinations, B different
- Choice RT for digit-key and light-key combinations (shown as a logarithmic function of number of trials (N_T) with N_A as parameter in Figs. 2 and 3) decreases with practice; least square fits are acceptable first approximations.
- There is a greater effect of practice for the digit-key than for the light-key combination.
- The light-key combination produces shorter RTs than the digit-key task over most of the ranges shown; however, extrapolation suggests a reversal of RTs before they reach their common limit.

Constraints

- The data from Ref. 1 showed the same trends as the other plotted studies, but were consistently lower and are shown corrected by 0.22 sec to match other data.

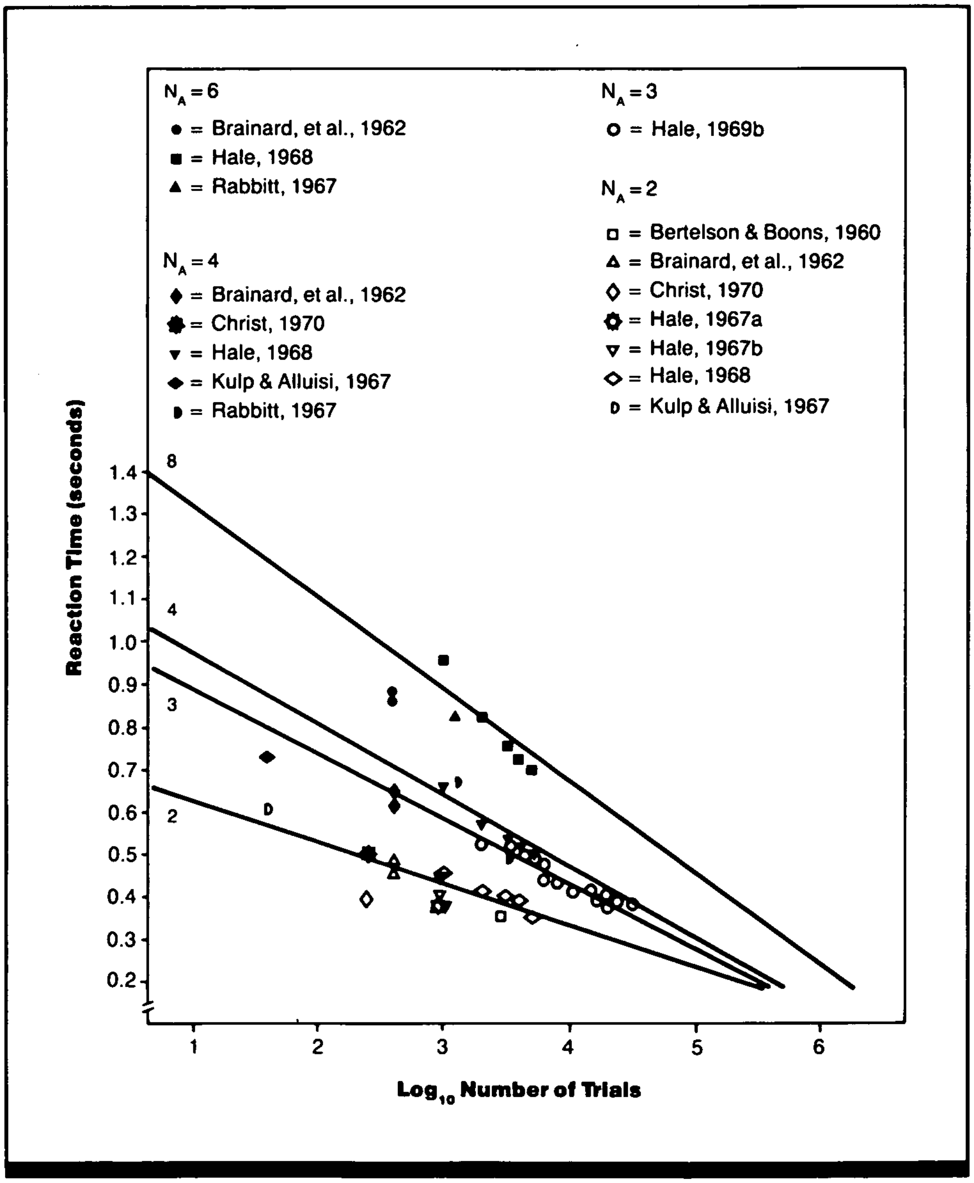

Figure 2. Choice RT as a function of practice for the digit-key task. See Ref. 2 for full citations of reviewed studies. (From Ref. 2)

Key References

1. Seibel, R. (1962). Discrimination reaction time as a function of the number of stimulus-response pairs and the self-pacing adjustment of the subjects. *Psychological Monographs, 76*, 42, (Whole No. 561).

*2. Teichner, W. H., & Krebs, M. J. (1974). Laws of visual choice reaction time. *Psychological Review, 81*, 75-98.

Cross References

9.111 Choice reaction time: effect of number of alternatives;

9.112 Choice reaction time: effect of probability of alternatives;

9.113 Choice reaction time: effect of stimulus probability and response-stimulus interval;

9.114 Choice reaction time: effect of warning interval on error;

9.115 Choice reaction time: effect of stimulus-response compatibility on error;

9.116 Choice reaction time: effect of stimulus-response compatibility;

9.118 Choice reaction time in the presence of conflicting information

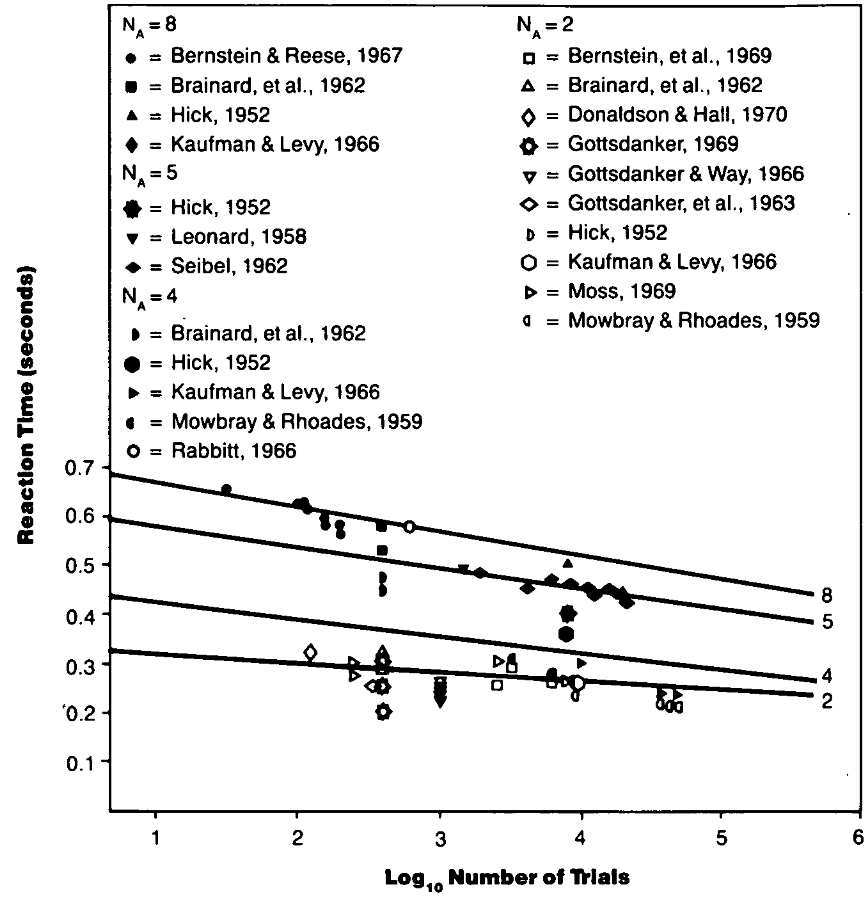

Figure 3. Choice RT as a function of practice for the light-key task. See Ref. 2 for full citations of reviewed studies. (From Ref. 2)

Notes

9.120 Reaction Time for Coupled Manual and Vocal Response: Effect of Stimulus Probability

Key Terms

Concurrent tasks; expectancy; inter-modality response; voice control

General Description

Reaction times (RTs) for naming responses are not influenced by the number of stimulus alternatives or by stimulus probability. In contrast, RTs for manual responses are strongly affected by these factors. When both types of response are made to the same stimulus event, the vocal response is delayed and the slopes of the functions relating stimulus probability and RT are similar.

Methods

Test Conditions

- Stimuli were letters L, N, R, and S (which begin with same phoneme for these French-speaking subjects), presented by eye-level Nixie indicator 80 cm from seated subject
- Vocal response was to name presented letter (timed via microphone 30 cm from subject); manual response was to press appropriate button with either left middle, left index, right index, or right middle finger for L, N, R, or S, respectively
- Stimulus probability conditions were equiprobable (0.25) or non-equally probable (0.50, 0.25, 0.125, and 0.125), counterbalanced across letters (Fig. 1)
- Onset of 0.50 sec warning light 1 sec before stimulus; 10-sec interval between presentations
- Three tasks (vocal only, manual only, both vocal and manual) per session; trials blocked by probability per task
- A monetary bonus given for RTs faster than the mean practice RT and errors penalized by deleting equivalent of two bonuses; subjects told total gain after each block, but no other information

Experimental Procedure

- Independent variables: response mode, response conditions, stimulus probability
- Dependent variable: RT
- Subject's task: for vocal response, detect and name the presented letter; for manual response, detect the presented letter and press the appropriate button
- 8 university students, some practice

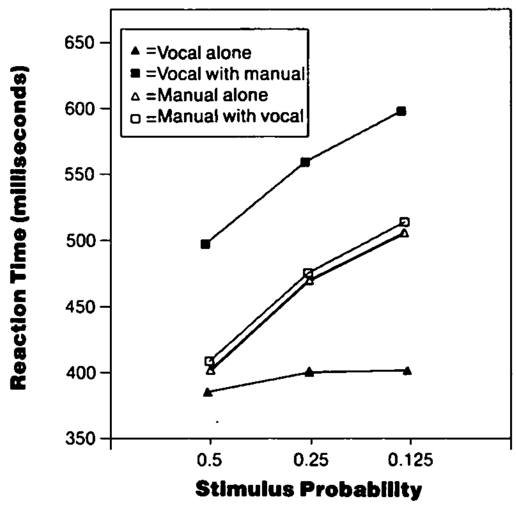

Figure 1. Reaction times for vocal or manual responses alone, and for each type of response in the presence of the other type, as a function of stimulus probability. (From Ref. 1)

Experimental Results

- For single responses, vocal RT is always shorter than manual RT; RTs for manual responses show strong effect of stimulus probability, but vocal responses are faster only for highly probable (0.50) stimuli. The slopes for the functions relating vocal and manual RTs to stimulus probability are different.
- When two responses are made, the vocal response is delayed and time-locked with the manual response; the slopes of the functions for vocal and manual RTs are identical. The correlations of manual and vocal latencies range from $r = 0.74$ to $r = 0.88$ (mean $r = 0.83$). For manual responses, the absolute RT values and the effect of stimulus probability are identical to those for single responses.

Variability

Bravet-Pearson correlation, analysis of variance, and post-hoc Duncan comparisons were used for data analysis. No mean square errors were reported.

Repeatability/Comparison with Other Studies

These effects are not easily changed by using different instructions. In a similar experiment with equiprobable stimuli (Ref. 1), subjects were (A) given the same instructions and tasks, (B) told to synchronize the vocal and manual responses, or (C) told to give full priority to the vocal response while doing as well as possible on the manual response. The results for Conditions A and B were similar to the first experiment; in Condition B, subjects did not succeed in following instructions and the vocal responses were delayed. In Condition C, the naming responses were given before the manual responses, but the RTs for both types of responses were much longer than in the reported experiment.

In other studies, stimulus probability affected naming responses in a five-choice RT task using numbers (CRef. 9.112). However, when motor preparation for speech was precluded in another study, the effects were small or nonexistent (Ref. 3).

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Constraints

• Naming a letter has a higher degree of stimulus-response compatibility than does pushing a button associated with the same letter. High stimulus-response compatibility decreases or eliminates the effect of increasing the number of alternatives (CRef. 9.116), and probability and number of alternatives are not independent.

• The Hick-Hyman law of choice reaction time (RT) is $RT = a + bH_S = a + bH_T$, where H_S is the amount of information (number of bits) in the stimuli and H_T is the amount of information transmitted. Under ideal choice RT conditions in which an observer always responds with the single response that is associated with each stimulus, $H_S = H_T = \log_2 N$, where N equals the number of alternative stimulus-response pairs. However, this equality does not hold when conditions are not ideal. Then RT is more accurately a function of the amount of transmitted information, rather than the number of alternative stimulus-response pairs. For details on the computation of H_T in this type of situation, see Ref. 2.

Key References

*1. Holender, D. (1980). Interference between a vocal and a manual response to the same stimulus. In G. E. Stelmach & J. Requin (Eds.), *Tutorials in motor behavior* (pp. 421-431). Amsterdam: North-Holland.

2. Kantowitz, B. H., & Sorkin, R. D. (1983). *Human factors: Understanding people-system relationships*. New York: Wiley.

3. Theios, J. (1975). The components of response latency in simple human information processing tasks. In P. M. A. Rabbitt, & S. Dornic (Eds.), *Attention and performance V* (pp. 418-440). London: Academic Press.

Cross References

9.112 Choice reaction time: effect of probability of alternatives;

9.113 Choice reaction time: effect of stimulus probability and response-stimulus interval;

9.116 Choice reaction time: effect of stimulus-response compatibility;

Handbook of perception and human performance, Ch. 30, Sect. 1.4

9.121 Interaction Among Multiple Stimuli and Responses

Situation	Effect	Source
Two stimuli, each requiring a separate response	1. The response to the second stimulus is delayed if the second stimulus occurs before the first response has been made	CRef. 9.107
	2. If the interval between stimulus onsets is brief, the first response is often delayed and grouped with the second response	CRef. 9.107
	3. Increasing the number of possible responses to the first stimulus delays the response to the second stimulus when intervals between stimulus onsets are brief	CRef. 9.107
	4. Increasing the number of possible responses to the second stimulus can delay the response to the first stimulus, but not always, even at brief intervals between stimulus onsets	CRef. 9.107
	5. Highly compatible pairings of stimuli and responses (e.g., naming a visually presented digit) can eliminate any delay of the response to the second stimulus only when the stimuli and response pairings are in different modalities	CRef. 9.107
Multiple stimuli and one response	1. Difficulty in discriminating among stimulus alternatives may increase the amount of interference	CRef. 9.117
	2. If a target stimulus does not have a unique feature (i.e., one that is not present in the distracting stimulus), the target is more difficult to locate (e.g., reaction time is longer)	CRef. 9.117
	3. A target stimulus defined by a conjunction of features (e.g., a red E versus a yellow F) can be more readily discriminated from backgrounds containing those features if the location of the target is known and the conjunctions are highly practiced.	CRef. 9.117
	4. Reaction times are slower if an irrelevant feature of a stimulus or spatially close object suggests a response that conflicts with the appropriate response	CRef. 9.118
	5. Redundant information that repeats the same information in a different form (e.g., words and pictures) may slightly decrease the reaction time for a response	CRef. 11.420
One stimulus and multiple responses	1. Multiple responses (e.g., vocal and manual) to a single stimulus may be temporally coordinated, even when the instructions encourage the subject to respond independently	CRef. 9.120
Overall guidelines	Interference among multiple stimuli and responses can be minimized if as many as possible of the following conditions are met.	
	1. Stimuli come through different modalities and their internal representations are in different systems (e.g., visual symbols and auditory words)	
	2. Response modes are different from one another	
	3. Stimulus-response pairings are highly compatible	
	4. The tasks are continuous and do not involve grouping of the stimuli	
	5. The tasks are not periodic, so that they do not entrain one another to the same periodicity	

Key Terms

Stimulus-response compatibility; stimulus-response pairing

General Description

In many natural settings an individual must often respond to simultaneously or nearly simultaneously occurring stimuli, decide which of several possible stimulus events actually occurred, or make multiple responses to a single stimulus. Interference may occur in stimulus processing, in linking stimuli and responses, and in producing responses. The table lists guidelines for understanding the effects of interference.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- The factors influencing simple and choice reaction times (e.g., stimulus or response probability) will also affect reaction time for multiple stimuli and responses.
- In addition to stimulus-response effects, motor control has certain limitations on response production that may slow reaction time as well as movement time (CRefs. 9.301, 9.305, 9.307).

Key References

*1. Keele, S. W. (1986). Motor control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive Processes and Performance*. New York: Wiley.

Cross References

9.107 Serial reaction time: effect of signal spacing;

9.110 Factors affecting choice reaction time;

9.117 Choice reaction time: detection of targets amid irrelevant stimuli;

9.118 Choice reaction time in the presence of conflicting information;

9.120 Reaction time for coupled manual and vocal response: effect of stimulus probability;

9.301 Maximum tapping speed: effects of age and sex;

9.305 Coordination of hand movements on timed tasks;

9.307 Hand and voice coordination;

11.420 Response time with redundant information

9.122 Interference Between Concurrent Tasks: Effect of Response Mode Similarity

Key Terms

Concurrent tasks; cross-modality effects; interference effect; psychological refractory period; sensory modality; voice control

General Description

When two tasks are performed concurrently, the amount of interference between them depends on the modalities of the two responses. For example, when the primary task is manual tracking (moving a lever to keep a dot on target), a secondary task requiring manual response with the other hand reduces accuracy more than a secondary task requiring a vocal response. Also, the timing of primary task performance is affected by the timing of a task involving a second manual response, but is independent of the timing of a secondary task involving a vocal response.

Applications

To optimize dual-task performance, the modalities of responses (as well as the modalities of the stimuli) must be considered.

Methods

Test Conditions

• Primary task was to keep a 1-mm diameter, horizontally moving dot close to a 4x1-mm stationary target at the center of a 35x30-cm screen; movement of dot determined by a control stick, 11 cm long and free to move in an arc of 24 deg on either side of vertical; dot accelerated 8 cm/sec^2 to the left when control stick was left of vertical and 10 cm/sec^2 to the right when control was to the right; dot did not change direction as soon as control stick reversed, but first decelerated to zero velocity; control stick had no zero position and was manipulated by preferred hand

• Secondary task was to identify a 250-msec, high (3000-Hz) or low (1000-Hz) tone (an easy task) either by pressing one of two keys under the first and second fingers of the non-preferred hand (manual response) or by saying "high" or "low" (vocal response); interstimulus intervals between tones varied randomly from 1.5-2.5 msec; tones played through loudspeakers and RT measured via throat microphone and voice key

Experimental Procedure

• Tracking task with or without two-choice RT task; each subject served only in vocal or manual response condition for secondary task

• Independent variables: time intervals established by successive left and right movements of tracking control lever for single and dual tasks, response modality of secondary task

• Dependent variables: probability of tracking response (a shift in direction by the control stick) occurring at a particular time interval before or after a secondary task response (data for last 25 sec of each run on the last 2 days were pooled into 50-msec intervals); integrated tracking error scores for the last 3 days of testing (unit of error is centimeter seconds off-target; minimum score is 35 because dot starts off target)

• Subject's task: for primary task, keep dot as close to the stationary target as possible by manipulating the control stick; for secondary task, identify high or low tone by either a button press or a vocal response; at end of each session, subject told total tracking error for the entire session

• 22 Naval personnel with extensive practice; 11 subjects each in vocal and manual response groups; 2 subjects dropped from manual condition because of poor performance

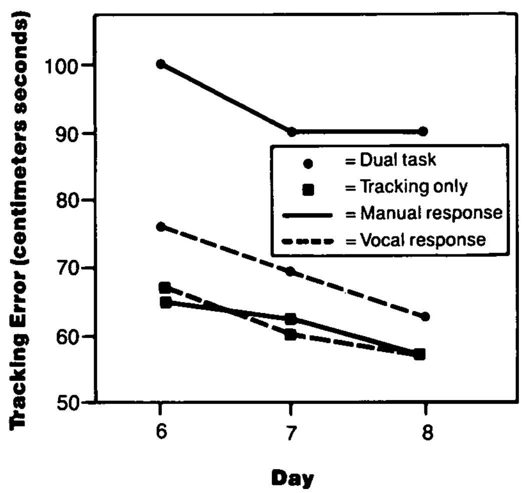

Figure 1. Tracking errors for a tracking task with and without a secondary task which required either a manual or a vocal response, over the last three experimental sessions (days). (From Ref. 2)

Experimental Results

• The vocal-response group and the manual-response group perform similarly on the tracking task alone (bottom two lines of Fig. 1).

• The tracking performance of the manual-response group deteriorates more with the addition of the secondary task than does the tracking performance of the vocal-response group ($p < 0.02$).

• The timing of the tracking responses and the vocal responses are independent; the dotted line in Fig. 2a indicates the probability distributions if responses are independent (based on the vocal response data).

• The timing of the tracking responses and the manual responses are not independent; the solid line for the data in Fig. 2b significantly differs from the dotted line, indicating independence.

Variability

Response patterns of individual subjects were similar to those for the group means (after 2 subjects were dropped from the manual-response condition). However, the necessity of dropping 2 subjects with 5 and 10 times the standard deviations of tracking errors of the other subjects, even after extensive practice, raises the issue of individual differences.

Repeatability/Comparison with Other Studies

The same conclusions were reached in a similar dual-task situation using different methods (Ref. 3). In a similar ex-

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

periment using easy or hard arithmetic secondary tasks, there was an overall decrement in tracking performance, but the primary and secondary responses were independent. The failure to abolish the psychological refractory period for two successive stimuli separated by a very brief interval except when stimulus and response modes were both differentiated (CRef. 9.107; Ref. 1) also indicates the strength of response mode interference.

Constraints

- The responses for the secondary task were always made with the non-preferred hand.

Key References

1. Greenwald, A. G., & Shulman, H. G. (1973). On doing two things at once: II Elimination of the psychological refractory period. *Journal of Experimental Psychology, 101*, 70-76.

*2. McLeod, P. (1977). A dual task response modality effect: Support for multiprocessor models of attention. *Quarterly Journal of Experimental Psychology, 29*, 651-667.

3. Wickens, C. D. (1976). The effect of divided attention on information processing in manual tracking. *Journal of Experimental Psychology, 2*, 1-13.

Cross References

9.107 Serial reaction time: effect of signal spacing;

9.108 Factors affecting simple reaction time;

9.115 Choice reaction time: effect of stimulus-response compatibility on error;

9.116 Choice reaction time; effect of stimulus-response compatibility;

9.120 Reaction time for coupled manual and vocal response: effect of stimulus probability;

9.121 Interaction among multiple stimuli and responses;

Handbook of perception and human performance, Ch. 30, Sect. 1.4

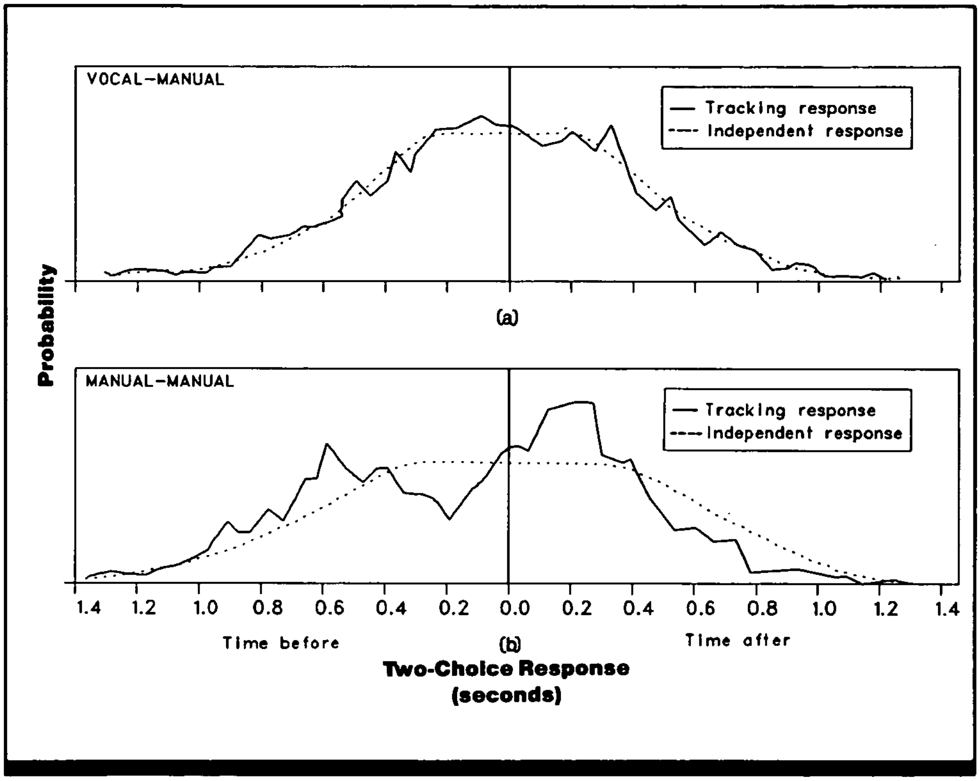

Figure 2. Probability distributions for tracking responses (reversals in control stick direction) as a function of the time interval between the tracking response and either the (a) vocal or (b) manual response for a secondary task. (From Ref. 2)

9.201 Fitts' Law: Movement Time as a Function of Distance and Accuracy

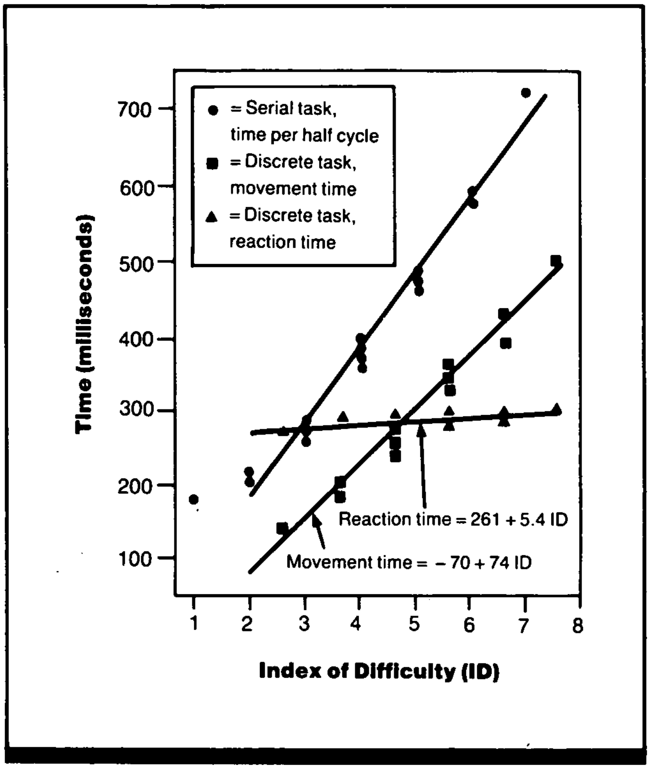

Figure 1. Reaction time (RT) and movement time (MT) as a function of index of difficulty for a serial (repetitive) and a discrete (single motion) task. (From Ref. 4, based on data from Refs. 2, 3)

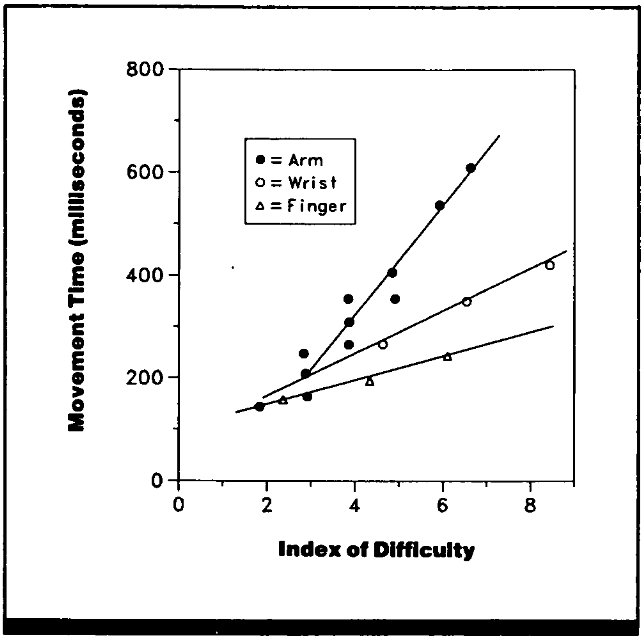

Figure 2. Movement time for finger, wrist, and arm as a function of index of difficulty. (From Ref. 6, based on Ref. 8)

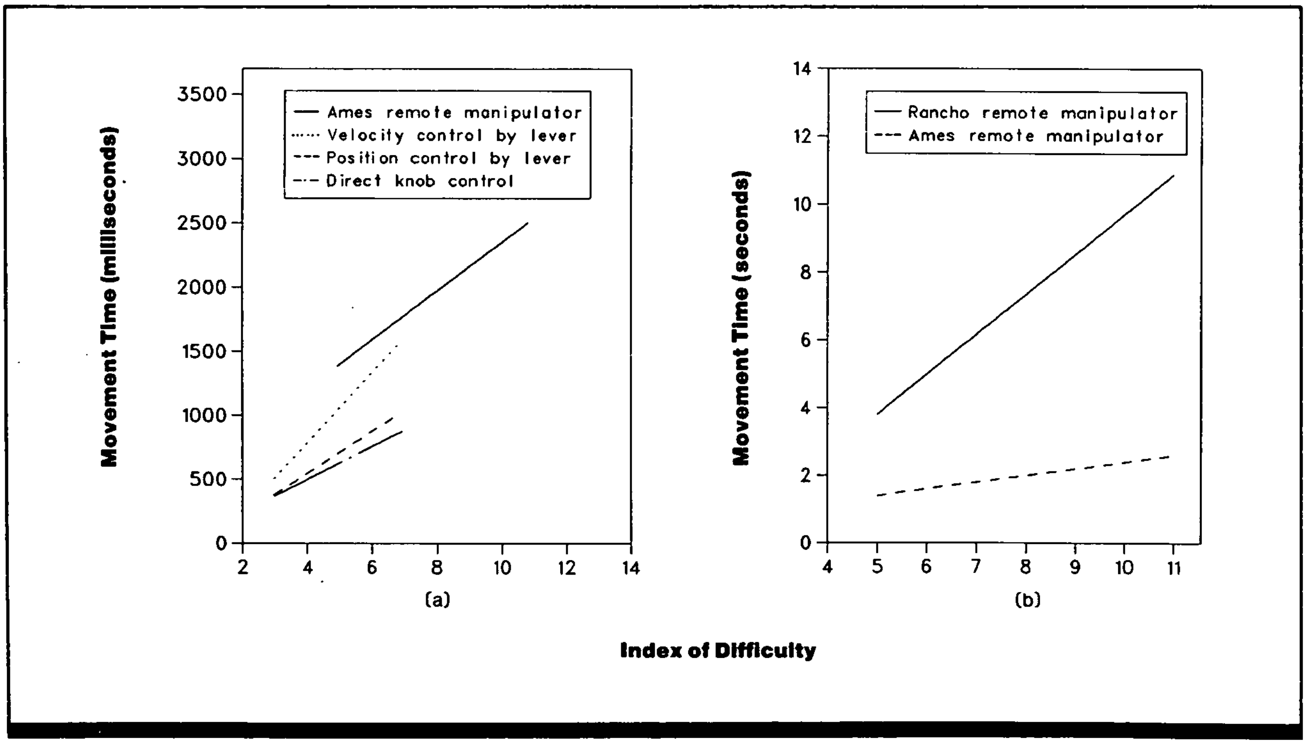

Figure 3. Movement time for (a) different types of controls and (b) for two remote controls as a function of index of difficulty. The Ames and Rancho remote manipulators are sleeves into which a subject's arm is placed, which simulate or mimic the subject's arm movements at a remote location. (From Ref. 6, based on data from Refs. 5, 7, 9)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Fitts' Law; index of difficulty; manipulation; movement time; skilled motor response; visual feedback

General Description

For movements in which visual feedback is used (e.g., reaching for an object), movement time (MT), which is the interval between initiation of movement and contact with the target, is directly related to distance and inversely related to target width (including permissible error tolerance); MT increases with the logarithm of distance (or amplitude) of the movement when target width (accuracy) is fixed, and decreases with the logarithm of target width when distance is fixed. Distance and width are compensatory (i.e., doubling of distance and width produces little change in MT). Fitts' Law, which can be used to estimate movement time for movements where accuracy is required, can be stated:

$$\mathrm{MT} = a + b \log_2 (2D/W)$$

where a and b are empirically derived constants, D is distance of movement, and W is target width (including total tolerance for error). The term $\log_2 (2D/W)$ is sometimes expressed as the index of difficulty (ID) measured in bits.

The constants a and b, representing the intercept and slope of the linear function, vary over tasks, targets, and subjects. Table 1 identifies functions relating Fitts' Law to MT for several tasks, describes the tasks and ranges of the independent variables, and lists references where more information is available.

Reaction time (RT), which is the time between the onset of the stimulus and the initiation of the movement response, is not related to either the movement distance or the target width (Fig. 1).

Table 1. Empirical validation of predicting movement time as a function of distance and target width.

Figure/ Reference	Task	Variable Ranges	Effects
Fig. 1/Ref. 2	Repetitive movement; tap stylus back and forth between targets (or transfer pegs to holes, or place washer over pegs)	Distance (D): 7.6-30.5 cm (3.0-12.0 in.) Width (W): 0.3-2.5 cm Index of difficulty (ID) = 2.58-7.58	Movement time (MT) increases 100 msec for each doubling of D/W ratio
Fig. 1/Ref. 3	Movement to target from home place; discrete movement	Distance: 7.6-30.5 cm Width: 0.3-2.5 cm ID = 2.58-7.58	MT increases as D/W ratio increases; see Fig. 1
Ref. 1	Subjects made a simple arm movement at rate that would be sustained in an industrial setting over the working day	No details available	Slope of MT is 180 msec per doubling of D/W ratio; an upperbound estimate
Fig. 2/Ref. 8	Stereo-microscopic movement of peg (1.1-mm diameter) between two holes (0.76-mm deep)	Distance (A): 0.25 cm (finger), 1.27 cm (wrist) Clearance (hole with peg): 0.076-1.07 mm ID = 2.25-8.38	26-msec slope for finger; 43-msec slope for wrist
	Repetitive tapping of arm (without scope)	Distance: 5.08-30.5 cm Width: 0.64-5.08 cm ID = 2.0-6.58	105-msec slope for arm
Comparison of human-controlled mechanical-response systems			
Fig. 3a/Ref. 7	Direct link between hand and rotary knob connected to cursor	ID = 3-7	Best of those tested
Fig. 3a/Ref. 5	Position control of a cursor on scope by lever	ID = 3-7	Position joystick better than velocity joystick
Fig. 3a/Ref. 5	Velocity control of a cursor on scope by lever	ID = 3-7	Position joystick better than velocity joystick
Fig. 3a/Ref. 9	Remote manipulation with an Ames master-slave arm	ID = 5-11	Worse than joystick
Fig. 3b/Ref. 9	Comparison of Ames and Rancho remote master-slave arms	ID = 5-11	Ames much better than Rancho

Constraints

- Fitts' Law is applicable to a wide range of tasks where precise movements are required, but does not apply to movements too brief to permit visual feedback (CRefs. 9.203, 9.210), does not relate MT to reaction time (CRef. 9.203), and offers no description of how visual feedback is used (CRef. 9.206).
- The relationships shown here are for initial estimates and general guidance only. Each application is unique and should be subject to verification, particularly where time-critical performance is required.
- When two hands must perform different tasks, MT for the hand performing the easier task (smaller ID) cannot be described by Fitts' Law because the harder task (larger ID) determines MT for both hands (CRef. 9.202).
- For subjects over 60 yrs old, the distance component increases in importance (Ref. 10).
- For movements under water, the distance component has a greater effect on MT than does the target width (CRef. 9.207).

Key References

*1. Bailey, G. R., & Presgrave, R. (1958). *Basic motion time study.* New York: McGraw-Hill.

*2. Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology, 47,* 381-391.

*3. Fitts, P. M., & Peterson, J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology, 67,* 103-112.

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*5. Jagacinski, R. J., Pepperger, D. W., Moran, M. S., Ward, S. L., & Glass, B. (1980). Fitts's Law and the microstructure of rapid discrete movements. *Journal of Experimental Psychology: Human Perception and Performance, 6,* 309-320.

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*9. McGovern, D. E. (1974). *Factors affecting control allocation for augmented remote manipulation.* Unpublished doctoral dissertation, Stanford University.

10. Welford, A. T., Norris, A. H., & Shock, N. W. (1969). Speed and accuracy of movement and their changes with age. In W. G. Koster (Ed.) *Attention and performance, II* (pp. 315). Amsterdam: North-Holland Publishing.

Cross References

9.202 One- versus two-handed teaching: effects of target distance and width;

9.203 Fitts' Law: movement and reaction time as a function of target distance and size;

9.206 Reaching hand movements: effect of varying visual feedback;

9.207 Control movement times underwater and on land;

9.210 Time and accuracy of fast control movements

Notes

9.202 One- Versus Two-Handed Reaching: Effect of Target Distance and Width

Key Terms

Coordinated hand movement; two-handed reaching

General Description

When both the left and right hands reach for targets at unequal distances from the body, the movements of the hands are coordinated; although the hands move at different speeds, the velocity and acceleration patterns of the hands are almost perfectly synchronized (Fig. 1). When one hand reaches over a long distance to touch a small target (the difficult task) and the other hand travels a short distance to touch a large target (the easy task), the reaction time (RT) is determined by the difficult task (Table 1). However, when both hands perform the same task, the RT is shorter for easier-task trials. Similarly, when only one hand is used, the easier tasks yield shorter RTs than the more difficult tasks. The pattern of results is the same for two-hand movements diverging to the right or left, movements from the periphery back to center, and movements to target positions in front of the body.

Methods

Test Conditions

- One or two targets 3.6- or 7.2-cm wide mounted on a 76-cm high table, with movements toward targets directed laterally away from the body, laterally toward the body, or toward targets directly in front of the body
- Home key(s) either 6 or 24 cm from target(s) pressed by index finger(s) until auditory signal indicated beginning of trial; target(s) then touched by index finger(s); warning light preceded signal with 1-3-sec variable interval

Experimental Procedure

- Independent variables: direction of movement (across experiments), distance to target and target size, one-handed (right or left) or two-handed movements
- Dependent variables: RT, except when index finger did not touch target and when RT was <90 or >600 msec; movement time; movements analyzed with 200 frames per sec cinematography
- Subject's task: touch target(s) with index finger(s) as quickly as possible after auditory signal
- 12 right-handed male students in each of three experiments (ages 18-25), with some practice; 1 subject dropped from first experiment because of excessive errors due to limited peripheral vision and 1 subject dropped from second experiment because of equipment malfunction

Experimental Results

- Difficult movements (long distance and narrow target) take longer than easy movements (short distances and wide target) for one-handed movements and for two-handed movements when both hands perform the same task.
- There are no differences in RT for one- and two-handed tasks of the same degree of difficulty. When two-handed movements are of unequal difficulty, the more difficult task determines the movement time; movement time for an easy task is longer when combined with a difficult task than when combined with a second easy task.
- For all two-handed movements in which the hands moved different distances, hand movements are simultaneously initiated and completed through synchronized acceleration and velocity.

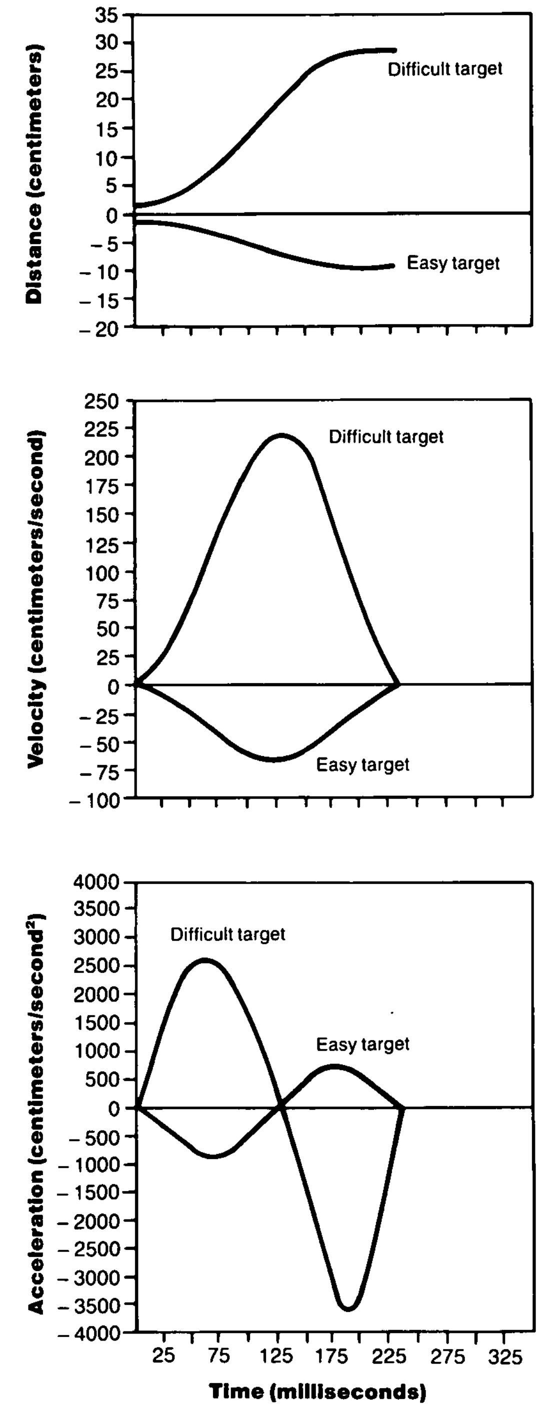

Figure 1. Displacement, velocity, and acceleration for each hand when one hand performs an easy reaching task and one hand performs a difficult reaching task (From Ref. 2)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Variability

No information about variability was given. All subjects served in all conditions.

Repeatability/Comparison with Other Studies

The same pattern of results was achieved when subjects were instructed to move the hands independently in two-handed movements. Instead of separating the movements, the movements of both hands were slowed.

Constraints

- It is unclear whether the synchronization of two-handed movements of unequal difficulty would break down with extensive practice.

Key References

1. Keele, S. W. (1986). Motor control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol II. Cognitive processes and performance*. New York: Wiley.

*2. Kelso, J. A. S., Southard, D. L., & Goodman, D. (1979). On the coordination of two-handed movements. *Journal of Experimental Psychology: Human Perception and Performance, 5*, 229-238.

Cross References

9.101 Reaction time tasks and variability;

9.109 Simple reaction time to visual targets;

9.203 Fitts' Law: movement and reaction time as a function of target distance and size;

9.208 Blind positioning accuracy: effect of target location;

9.305 Coordination of hand movements on timed tasks

Table 1. Movement time and reaction time for single arm and two arm movements (From Ref. 1, based on Ref. 2)

Number of Arms Moved/ Number of Identical or Different Targets	Target Distance/ Width	Movement Time (msec)	Reaction Time (msec)
One arm/One target	Short distance, wide target	80	212
One arm/One target	Long distance, narrow target	155	219
Two arms/Two identical targets	Short distances, wide targets	87	222
Two arms/Two identical targets	Long distances, narrow targets	168	238
Two arms/Two different targets	Short distances, wide targets	137	244
Two arms/Two different targets	Long distances, narrow targets	156	239

9.203 Fitts' Law: Movement and Reaction Time as a Function of Target Distance and Size

Key Terms

Fitts' Law; movement time; visual feedback

General Description

For movements over a distance to a target, movement time (MT) increases as distance (amplitude) increases, and decreases as target size (accuracy) increases (Fig. 1), so that MT can usually be described as a ratio of amplitude and accuracy (Fitts' Law, CRef. 9.201). Over the range of movements that are long enough to permit the use of visual feedback, reaction time (RT) is independent of target size (Table 1). For movement over distances so short that visual feedback cannot be utilized, MT and RT both decrease as target size increases, but the function relating MT to log target diameter becomes less linear as movement becomes shorter (Fig. 1). This failure of Fitts' Law and the increase in RT for short movements suggest that short movements are preplanned and that planning for complex movements takes longer (Table 1).

Methods

Test Conditions

- Subject seated at table in sound isolation chamber; center rest position on table was 2 mm in diameter and contained an indentation for tip of stylus (a modified ballpoint pen of 9.7-g mass)
- Targets on table were brass circles with diameters of 2, 4, 8, 16, 32, or 64 mm; distance from rest position to left or right target was 2, 11, 70, or 336 mm
- For a trial, central green light in a line parallel to and 25 cm beyond the pathway between the targets came on as a warning signal, followed by random foreperiod of 1.0, 1.3, or 1.6 sec; then a white light to left or right informed subject to move stylus to left or right target and served as cue to respond; RT measured from onset of white light until stylus left rest position; MT measured from time stylus left rest position until target contact

Experimental Procedure

- Two-alternative choice RT
- Independent variables: target diameter, target distance
- Dependent variables: RT, MT, and error rate
- Subject's task: move stylus from rest position to target signaled by white light as rapidly as possible while keeping errors at 10%; visual feedback provided for missed targets and trials were rerun later
- Subjects were told to go faster or be more careful in practice session to keep error rate at ~10%
- 8 right-handed undergraduates

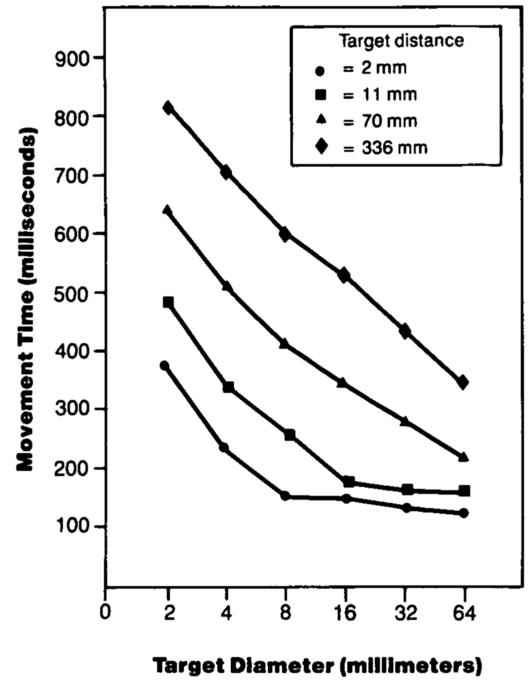

Figure 1. Movement time as a function of target diameter. Movement distance is the parameter for each curve. (From Ref. 4)

Experimental Results

- There is a significant positive correlation between RT and MT across subjects [$r(6) = 0.822, p < 0.05$].
- MT increases with increasing movement distance ($p < 0.001$) and decreases with increasing target diameter ($p < 0.001$). However, MT has a significant length by diameter interaction ($p < 0.001$), reflecting nonlinearity for shorter lengths.
- RT is independent of distance, but decreases as diameter increases ($p < 0.001$). However, RT has a significant length by diameter interaction ($p < 0.001$), indicating RT for longer movements is relatively independent of diameter.
- Nonsignificant negative correlations between error rate and MT and error rate and RT per subject indicate a speed and accuracy tradeoff; smaller targets and longer distances tended to yield higher error rates (mean = 7.86%).

Variability

Error rate for individual subjects varied from 3.13-9.38%.

Repeatability/Comparison with Other Studies

For longer movements, other studies have also found that RT is independent of target diameter (Ref. 1, CRef. 9.201).

In a second experiment (Ref. 4), turning off the illumination somewhat disrupted a 2-mm movement (10% target misses), but a 336-mm movement was extremely difficult (93% target misses). It is unclear whether the disruption of short movements is a general disruption or indicates the presence of feedback control.

Similarly, turning off the lights, so that subjects had no visible feedback, affected movement accuracy reported in Ref. 2. Movements as brief as 190 msec were not more accurate when the lights were left on, but movements lasting 260 msec or longer (over the same distances) were facilitated.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Nonlinearity of MT for short movements is also related to speed of movement and to force employed (CRef. 9.210).

Key References

1. Glencross, D. J. (1973). Response complexity and the latency of different movement patterns. *Journal of Motor Behavior, 5,* 95-104.

2. Keele, S. W. (1986). Motor control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance*. New York: Wiley.

3. Keele, S. W., & Posner, M. I. (1968). Processing of visual feedback in rapid movements. *Journal of Experimental Psychology, 77,* 155-158.

*4. Klapp, S. T. (1975). Feedback versus motor programming in the control of aimed movements. *Journal of Experimental Psychology, 104,* 147-153.

Cross References

5.1107 Adaptation to prismatic displacement of the visual field: effect of feedback delay;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

9.111 Choice reaction time: effect of number of alternatives;

9.112 Choice reaction time: effect of probability of alternatives;

9.114 Choice reaction time: effect of warning interval on error;

9.201 Fitts' Law: movement time as a function of distance and accuracy;

9.206 Reaching hand movements: effect of varying visual feedback;

9.210 Time and accuracy of fast control movements

Table 1. Movement time (MT) and reaction time (RT) in milliseconds as a function of movement length and target diameter. (From Ref. 2, based on Ref. 4)

Distance		Small (2-4 mm)	Medium (8-16 mm)	Large (32-64 mm)
Short (2 mm)	MT	290	150	140
	RT	347	327	304
Long (336 mm)	MT	760	560	390
	RT	327	329	323

Movement time increases as target size diminishes for both short-distance and long-distance movements. The short-distance movements are not under visual feedback control and, for them, longer lasting movements take longer to program, as reflected in reaction times. The long-distance movements are under feedback control and movement duration is not related to reaction time.

9.204 Blind Positioning: Effect of Prior Target Exposure

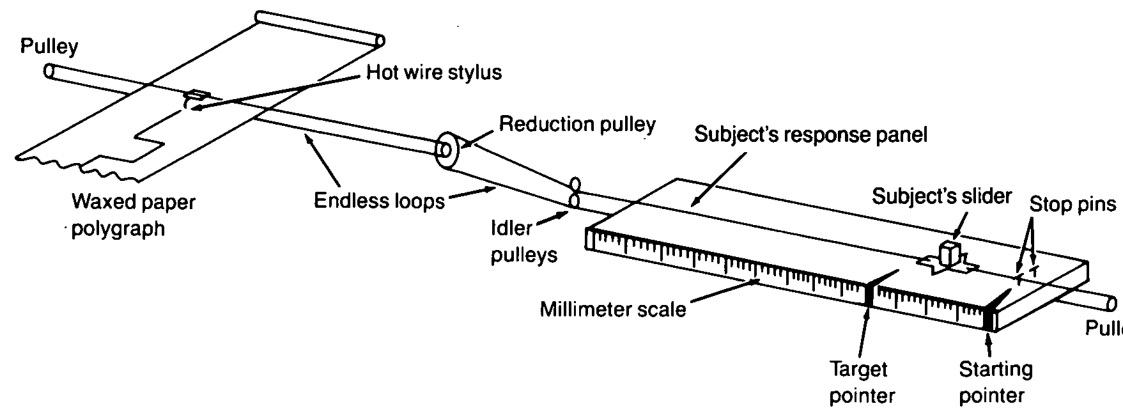

Figure 1. Schematic diagram of apparatus used to measure positioning accuracy. After apparatus was briefly illuminated, subject moved slider from starting pointer in dark to remembered position of target pointer. Subject's orientation with respect to response panel was varied to produce one of six movements. Subject judged outward movements from near the body to far (H:NF) or inward movements from far to near (H:FN), movement from a point central to the body to the right (H:CR) or from a point right of the center to center (H:RC), and (with response panel mounted vertically) judged movement upward from the bottom of the track to the top (V:BT) or from the top of the track to the bottom (V:TB). (Adapted from Ref. 1)

Key Terms

Blind positioning; movement accuracy; position estimation; target acquisition; visual feedback

General Description

When required to estimate the position of a previously seen target by moving a slider in the dark to the target position, subjects tend to overestimate short distances and underestimate long distances. With increasing distance, relative error decreases and variability increases.

Methods

Test Conditions

- Subject moved slider along a track in the dark
- Two pointers indicated starting and target positions; apparatus illuminated by 100-watt lamp for 2.5 sec, after which subject moved slider held between right thumb and forefinger to remembered position of target pointer
- Track located in either a vertical or horizontal plane and positioned to require one of six kinds of movement: movement upward from the bottom of the track to the top or from the top of the track to the bottom; outward movement from near the body to far or inward movement from far to near; or movement from a point central to the body to the right or from a point right of the center to center
- Target distances were 0.6, 2.5, 10, or 40 cm

Experimental Procedure

- Method of adjustment
- Independent variables: distance of target, direction of target relative to body
- Dependent variable: positioning accuracy as measured by mean constant error (difference between target position and matched position)
- Subject's task: position slider in the dark to remembered position of a previously seen target
- Ten consecutive trials per condition
- 24 subjects; subjects were randomly assigned to one of four target distance conditions for each of six target direction conditions; each given ten practice trials for a target distance of 15 cm

Experimental Results

- The distance of a previously seen target is overestimated at short distances and underestimated at long distances (as judged by the subjects' ability to move a slider to the remembered position of the target) in the dark. However, when moving the slider vertically from top to bottom, subjects overestimate distance regardless of actual target distance.
- The error in judged distance as a percentage of actual distance decreases with increasing target distance.
- Positioning reactions involving movements away from the body tend to be more accurate than those requiring movements toward the body.

Variability

The variability of judged distance increases with increasing distance. Standard deviations of distance judgment are plotted in Fig. 2b.

Repeatability/Comparison with Other Studies

Similar results for shoulder movement are reported in Ref. 2.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Because light to illuminate target remained on only briefly after a period in the dark, results may reflect lack of depth perception cues rather than kinesthetic effect.
- A within-subject design with more subjects per condition would permit greater generalization of findings.
- This study does not measure the ability to discriminate accurately the direction and extent of a limb's movement.

Key References

*1. Brown, J. S., Knauft, E. B., & Rosenbaum, G. (1948). The accuracy of positioning reactions as a function of their direction and extent. *American Journal of Psychology, 61*, 167-182.

2. Caldwell, L. S. (1956). *The accuracy of constant angular displacement of the arm in the horizontal plane as influenced by the direction and locus of the primary adjustive movement* (Rep. No. 233). Fort Knox, KY: Army Medical Research Laboratory.

Cross References

3.309 Accuracy of horizontal arm positioning: effect of direction and angular placement;

5.1010 Cross-modal versus intramodal perception of distance and location;

5.1107 Adaptation to prismatic displacement of the visual field: effect of feedback delay;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions

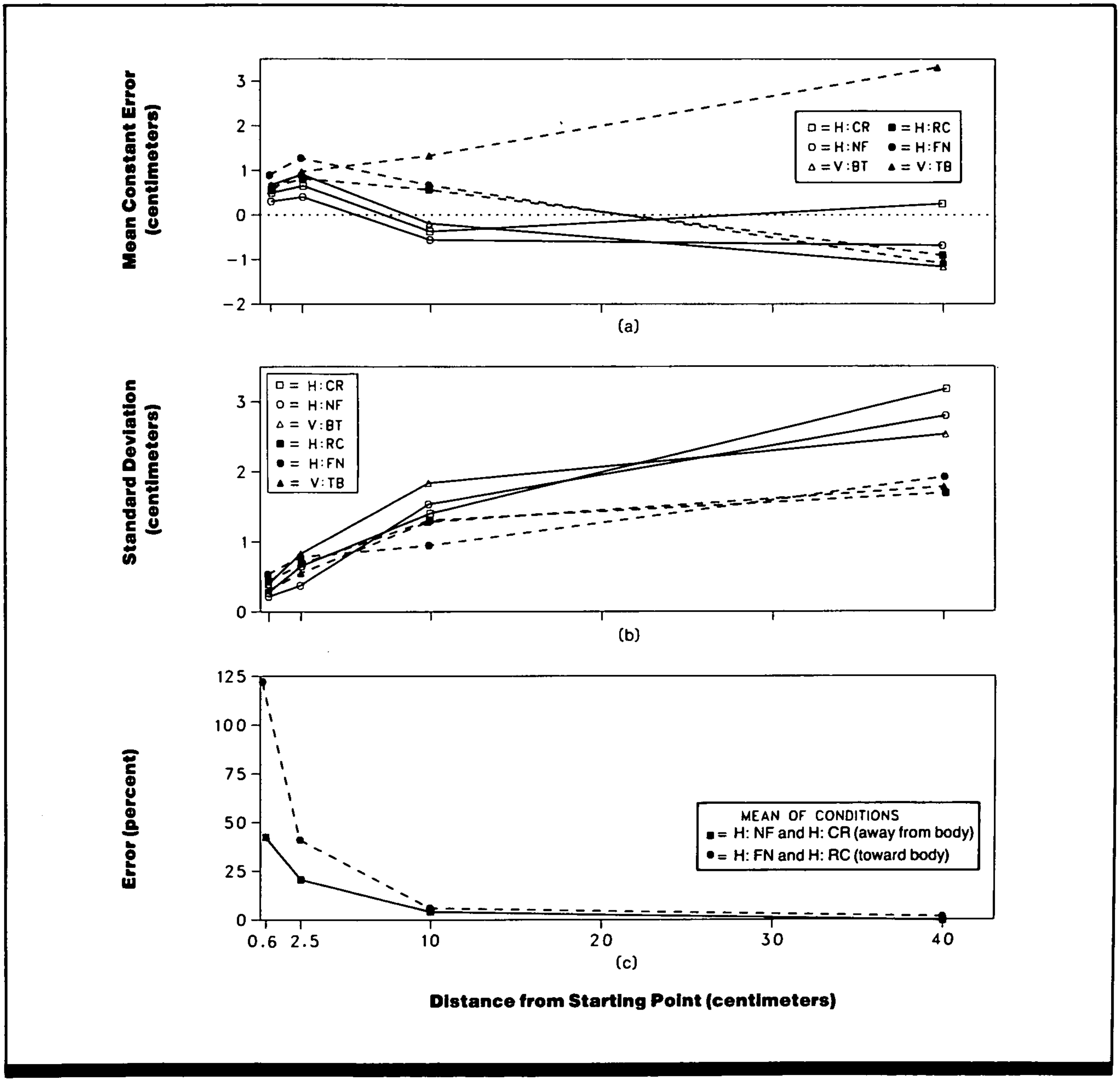

Figure 2. Accuracy of positioning slider on a track as a function of distance from the starting point for various movement directions. (a) Mean constant error, (b) standard deviation, and (c) percentage error as a function of target distance. Positive error indicates overestimation of distance. (From Ref. 1)

9.205 Control Movements: Effect of Direction

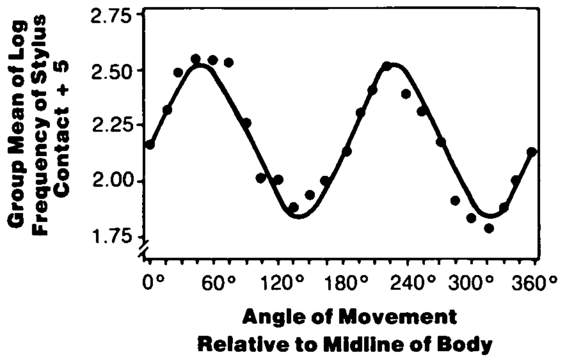

Figure 1. Frequency of errors (contact of stylus with side of track) in pursuit motor task, as a function of direction of movement with respect to midline of body (0 deg). (From Ref. 2)

Key Terms

Control design; control movements; controller tasks; motor pursuit; tracking

General Description

Precision of linear pursuit movements is a function of the angle from the body at which the movement is made. When the movement is directly away from the midline of the body, the 0 deg (or 360 deg) condition is represented; tracking performance is best when the angle from the body at which the movement is made is 135 deg or 315 deg.

Applications

Designing controls that involve using precise arm movements.

Methods

Test Conditions

- 35.0-cm-long by 0.4-mm-wide track resting on glass plate with a small cylindrical target traveling underneath the glass plate at constant velocity of 3.0 cm/sec
- Metal-tipped stylus to be moved in track above target without touching sides of track
- Angle of track adjusted for 24 different angles of movement at 15-deg intervals between 0 and 360 deg
- Subjects sat in tank driver's seat with harness about trunk to keep right shoulder in fixed position

Experimental Procedure

- Latin square design
- Independent variable: angle of track relative to midline of body
- Dependent variable: frequency of stylus contact with sides of track
- Subject's task: track target without touching sides of track
- 48 male subjects, undergraduate, right-handed, practiced

Experimental Results

- Precision of tracking performance is a cyclical function of angle, with best performance at 135 and 315 deg.

Variability

Mean square error for frequency of errors in 360 trials of track movements is 0.0356.

Repeatability/Comparison with Other Studies

This experiment confirms and extends the findings of Ref. 1.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Many factors, such as amount of practice, the visual field (the subject's view of his hand, arm, stylus, target, and track), the muscle-groups involved, the measure of precision, the magnitude of errors or their direction, various aspects of the target, and the distribution of practice, can influence pursuit movements or their measurement, and must be considered in applying these results.

Key References

1. Corrigan, R. E., & Brogden, W. J. (1948). The effect of angle on precision of linear pursuit movements. *American Journal of Psychology, 61*, 502-510.

*2. Corrigan, R. E., & Brogden, W. J. (1949). The trigonometric relationship of precision and angle of linear pursuit movements. *American Journal of Psychology, 62*, 90-98.

Cross References

9.208 Blind positioning accuracy: effect of target location

9.206 Reaching Hand Movements: Effect of Varying Visual Feedback

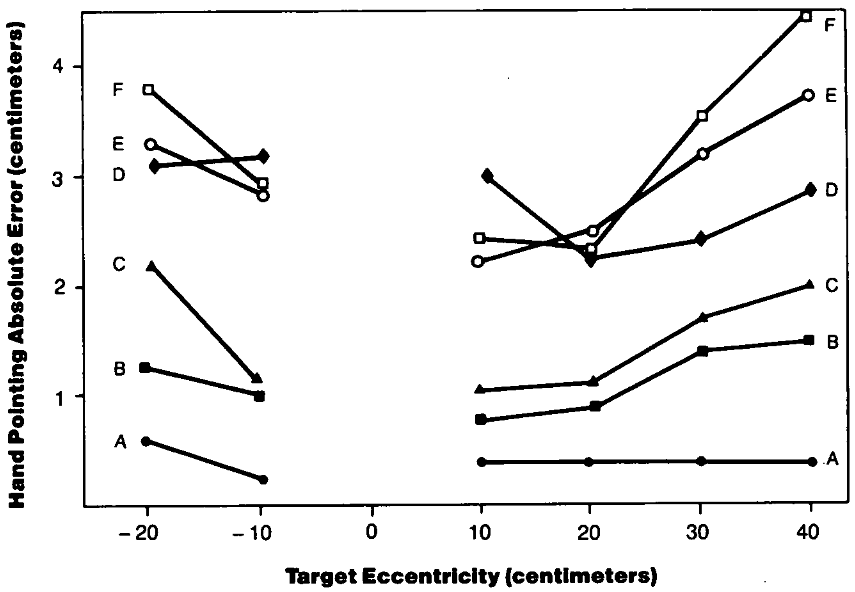

Figure 1. Absolute error (distance from target) when pointing to a target under various conditions of visual feedback. A: hand always visible, free eye movements, target present; B: hand always visible, center-fixated gaze; C: hand always visible, free eye movements, target disappears; D: hand never visible, free eye movements, target present; E: hand never visible, center-fixated gaze; F: hand never visible, free eye movements, target disappears. (From M. Jeannerod & C. Prablanc, Visual control of reaching movements in man, J. E. Desmedt (Ed.), *Motor control mechanisms in health and disease.* Copyright 1983 by Raven Press, New York. Reported with permission)

Key Terms

Movement time; reaching hand movement; visual feedback

General Description

Under natural conditions, moving a hand to a target involves seeing the hand and the target and moving the eyes between them. Changing the conditions of visual feedback while manipulating target position makes it possible to define the effect of feedback on accuracy, duration, and latency of hand movements. Reaction time (RT, or latency to initiate the movement), movement time (duration of the movement), and accuracy are all affected by target eccentricity (distance of the target from the **medial plane**). Movement time increases as target eccentricity increases, but is independent of visual feedback condition. RT and accuracy are best when the subject can see both the hand and the target and move the eyes between them. Also, RT is shorter and accuracy is greater when the hand can be seen at least part of the time.

Methods

Test Conditions

- Subject seated with head fixed in place; binocular view of virtual image of target (random pattern of red-emitting diodes) through semireflecting mirror; presence or absence of illumination within box-like apparatus determined whether subject could see hand
- Hand-illumination conditions: illuminated throughout movement, hand never illuminated, hand illuminated before initiation of movement, but not during movement, or hand illuminated during movement, but not while in resting position before movement
- Within each hand-illumination condition, subject instructed either to move eyes freely, not to move eyes, or to move eyes freely while the target disappeared at the onset of a saccadic eye movement toward it
- Illumination controlled by electronic shutter with response time of 5 msec; binocular eye movement recorded by **electro-oculography** (EOG)
- Hand position recorded via a thimble on subject's right forefinger that indicated hand position when in contact with plane of target, which was covered with isotropic resistive paper; logic pulses generated at beginning and end of movement also via the thimble
- For each trial, target jumped from position on median plane to a randomly selected position either 10, 20, 30, or 40 cm to right or 10 or 20 cm to left, and then back to center position

- For condition of no eye movement, subject continuously fixated another light located 2 mm ahead of center target position
- 5-sec interstimulus interval with random variation of 1 sec

Experimental Procedure

- Independent variables: target location, eye movement condition, hand illumination condition
- Dependent variables: latency and duration of first saccade after stimulus presentation (RT), eye position after first saccade, latency of hand movement (RT), hand movement time, and hand position
- Subject's task: keep eye and hand on target at center position, then keep eye and hand on target at its left or right position, then return to original position when target returned to or reappeared at its center position; for one eye-movement condition, eyes were fixated at center position at all times
- 8 adult subjects

Experimental Results

- Hand RT is shortest when the hand is seen all the time, longest when the hand is never seen, and intermediate for the other illumination conditions. (RT for each condition not given.)
- Hand and eye RT both increase as target distance increases, but they are generally not correlated with each other.
- Hand-movement time increases as target distance increases, but is independent of visual feedback condition.
- Figure 1 shows that there are fewer errors when the hand is visible at all times (lines A, B, and C in Fig. 1) than when hand is never visible (lines D, E, and F). Within the hand-illumination condition, errors are greater when the target is not visible after the first saccade begins (lines C and F). Freedom to move the eyes interacts with the hand-illumination condition; when the hand is visible, there are fewer errors with free eye movement (line A) than with a centrally fixated gaze (line B), but the opposite is true when the hand is not visible (lines E and D).
- There are fewer errors when the hand is visible either before or during its movement than when the hand is never visible.

Variability

Variance decreased as accuracy increased.

Repeatability/Comparison with Other Studies

Longer movement for a longer distance at constant target size is well supported (CRef. 9.201). Visual feedback can be utilized if it is available only during the final 135 msec of a movement (Ref. 1).

Constraints

- Other studies have not found a relationship between RT and distance (CRefs. 9.201, 9.203).
- The right hand was always used and hand dominance is not reported.

Key References

1. Carlton, L. G. (1981). Processing visual feedback information for movement control. *Journal of Experimental Psychology: Human Perception and Performance, 7,* 1019-1030.

*2. Jeannerod, M., & Prablanc, C. (1983). Visual control of reaching movements in man. In J. E. Desmedt (Ed.), *Motor control mechanisms in health and disease.* New York: Raven Press.

Cross References

5.1107 Adaptation to prismatic displacement of the visual field: effect of feedback delay;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

9.201 Fitts' law: movement time as a function of distance and accuracy;

9.203 Fitts' law: movement and reaction time as a function of target distance and size;

9.204 Blind positioning: effects of prior target exposure;

9.210 Time and accuracy of fast control movements

9.207 Control Movement Times Underwater and on Land

Key Terms

Control movements; Fitts' Law; movement time; underwater control; visual feedback

General Description

Fitts' Law (CRef. 9.201) describes movement time (*MT*) as constant for any given ratio of movement amplitude (or distance) and target width (or accuracy). Movements guided by visual feedback (CRef. 9.206) are governed by two separate processes, a fast process for covering distance and a slower process for zeroing in on the target. Thus, Fitts' Law can be reformulated as

$$MT = a + b \log_2 A - c \log_2 W$$

where A is movement amplitude and W is target width. The slope coefficients b and c do not significantly differ from one another for movements on land, but b is greater than c for underwater movements. Thus the distance component A contributes more to movement time for underwater actions than does the target-width component W; increasing distance slows movement more than decreasing target width for underwater movements. Therefore the function for land movements in Fig. 1 is almost linear, but the corresponding function for underwater movements illustrates the unequal effects of the two components.

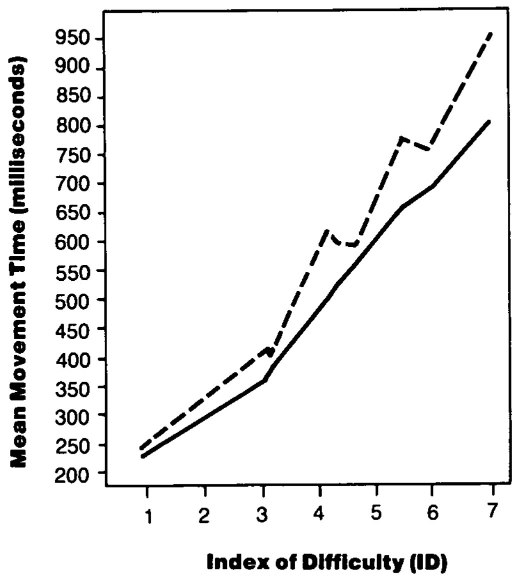

Figure 1. Mean times for movements on land (solid line) and underwater (dotted line) as a function of task difficulty. ID is a measure of task difficulty based on the amplitude/width ratio. (Data from Ref. 3)

Methods

Test Conditions

- For both land and water, pairs of targets marked on thin sheets of clear plastic secured to top of white table; each pair of targets separated by 50, 120, or 260 mm; target widths of 2, 6, or 15 mm
- For each subject, two sessions (7 days apart) of four sequences (land, water, water, land) of nine intertarget distance/target width ratios; 2-min rest or four 20-sec trials of a secondary task to improve accuracy between two underwater sequences
- Both on land and in water, subject wore full SCUBA equipment with a T-shirt and large plastic bag (rather than wet suit); subject's head ~15-20 cm below water surface in a well-lighted corner of heated pool; on land, subject sat on broad bench to support air tanks
- Subjects: experienced and novice SCUBA divers
- 20-sec trials and 10-sec intertrial intervals

Experimental Procedure

- Independent variables: session location (on land or under water), distance/target width ratio, SCUBA diving experience, underwater between-session activity (rest or secondary task)
- Dependent variable: movement time (*MT*), calculated as number of movements (targets tapped) per sec
- Subject's task: tap alternate targets of a pair with featherless dart as often as possible while maintaining <5% error (misses)
- 9 experienced and 11 novice SCUBA divers (ages 18-24) as subjects, with some practice

Experimental Results

- Movement time either on land or under water can be described as constant for any given ratio of movement distance (amplitude A) and target width (W).
- For the underwater task, changes in the distance component A more strongly affect RT than do changes in target width W (the slope coefficient for distance is much larger than the slope coefficient for target width). On land, the effects of distance and target width are approximately equal.
- Movements under water are much slower than similar movements on land. The mean RTs for the four sequences (land 1, water 1, water 2, land 2) are 543, 608, 582, and 502 msec, respectively; all differences are significant ($p < 0.05$).
- Performance improves significantly with practice, particularly on land, but additional testing suggests that the improvement is an adaptive effect from water to land.
- There are no significant differences between novice and experienced divers, and performing the secondary task between underwater sequences does not affect reaction time.

Variability

A repeated-measures analysis of variance was used; no mean square errors were reported.

Repeatability/Comparison with Other Studies

Direct support for the two-component theory has been provided under other circumstances (Ref. 1 and CRef. 9.206).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Beggs, W. D. A., & Howarth, C. I. (1970). Movement control in a repetitive motor task. *Nature, 225*, 752-753.

2. Kerr, R. (1973). Movement time in an underwater environment. *Journal of Motor Behavior, 5*, 175-178.

*3. Kerr, R. (1978). Diving, adaptation, and Fitt's Law. *Journal of Motor Behavior, 10*, 255-260.

Cross References

5.1124 Effect of underwater environments on perception;

5.1125 Underwater visual adaptation: effect of experience;

5.1126 Adaptation after prolonged exposure to an underwater environment;

9.201 Fitts' Law: movement time as a function of distance and accuracy;

9.202 One- versus two-handed reaching: effect of target distance and width;

9.204 Blind positioning: effect of prior target exposure;

9.206 Reaching hand movements: effect of varying visual feedback

9.208 Blind-Positioning Accuracy: Effect of Target Location

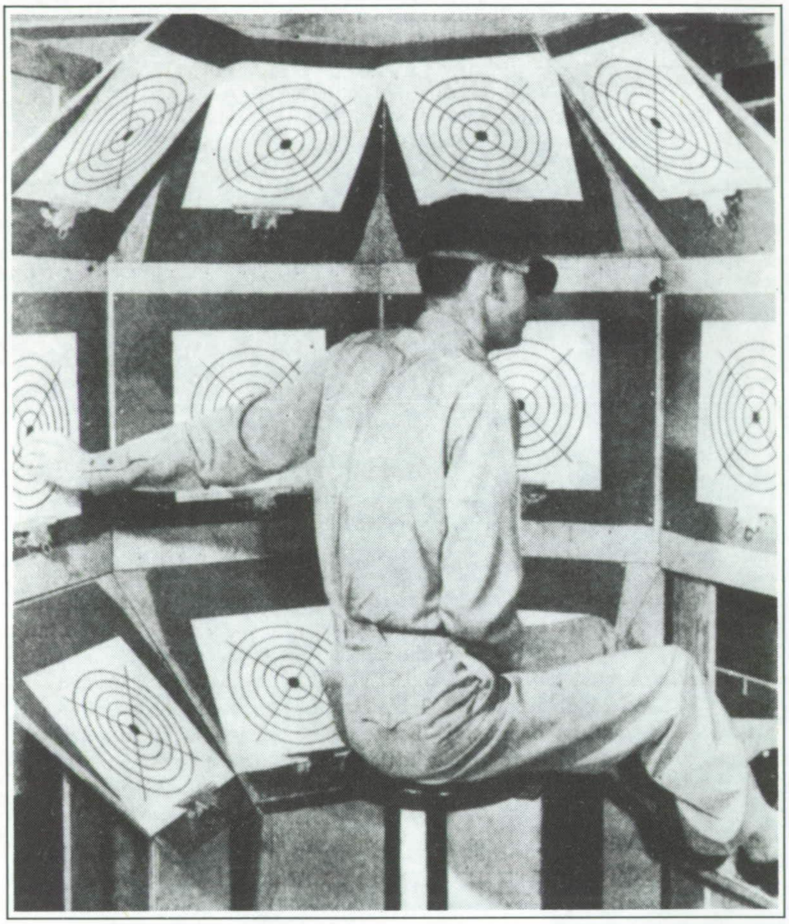

Figure 1. Experimental setup for studying blind-positioning in movements. (From Ref. 2)

Key Terms

Blind positioning; free positioning; restricted positioning; visual feedback

General Description

Blind-positioning movements, which are manipulations of controls without the use of vision to guide the movements, may be either restricted or free. In restricted movements, a knob or lever already in contact with the hand is moved a certain distance; in free-positioning movements, which are common in flight conditions, the operator is required to both locate and operate the control. Accuracy of such movements is best when targets are directly in front of the operator, and error increases as targets are placed more toward the periphery. Accuracy is also better for targets at or below shoulder height than for targets above the head. A practical rule derived from the average errors shown in Table 1 is that controls must be spaced ~15.24-20.32 cm (6-8 in.) apart in the preferred area (in front of the operator) and further apart ~30.48-40.64 cm (12-16 in.) in the areas to the back and sides of the operator.

Methods

Test Conditions

- Target positions were well learned
- Subject seated in experimental enclosure; fixated on red light and wore red goggles so that only red light was visible
- Targets were 76.2 cm from a reference point between subject's shoulders; positioned at 0, 30, 60, or 90 deg to left or right and either above subject's head (U), at shoulder height (C), or below subject's waist (D) (Fig. 1)
- Each of 20 targets had letter label known to subject

Experimental Procedure

- Independent variable: target position
- Dependent variables: accuracy (average error from mark to bull's-eye), direction of error (number of errors in each quadrant of target)
- Subject's task: reach for the target whose letter was spoken by experimenter and put mark as close as possible to the bull's-eye
- Unknown number of pilots as subjects

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Accuracy is best for targets directly in front of subject and at shoulder height; average error in this position is 5.33 cm.
- Accuracy is almost as good directly in front of and above subject's head; average error in this position is 6.4 cm.
- Accuracy decreases as target becomes more peripheral.
- For targets offset toward the periphery, average error is generally lower for targets below waist level than for those at shoulder level; average error is generally equal or lower for targets at shoulder height than for those above subject's head.
- An analysis of the direction of errors (shown in Fig. 2, with size of circle corresponding to number of errors in each quadrant of each target) shows that subjects tend to undershoot lower targets at the extreme right and left positions and overshoot upper targets.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Absolute error increases as targets are placed more peripherally, when eyes are not free to follow trajectory of movement.

Constraints

- Accuracy was the only performance measure; relative time for reaching different positions was not considered.
- In a real-world situation, operators might use peripheral vision to guide movements to learned locations, so the recommended spacings may be too conservative.

Key References

*1. Chapanis, A., Garner, W. R., & Morgan, C. T. (1949). *Applied experimental psychology: Human factors in engineering design* (pp. 264-296). New York: Wiley.

*2. Fitts, P. M. (1947). A study of location discrimination ability. In P. M. Fitts (Ed.), *Psychological research on equipment design* (pp. 207-217). Washington, DC: U.S. Government Printing Office.

3. Keele, S. W. (1986). Motor control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and peformance*. New York: Wiley.

Cross References

5.1107 Adaptation to prismatic displacement of the visual field: effect of feedback delay;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

9.204 Blind positioning: effect of prior target exposure;

9.206 Reaching hand movements: effect of varying visual feedback;

9.210 Time and accuracy of fast control movements

Table 1. Average error in centimeters of positioning movements with vision. (From Ref. 3)

Plane of movement	Angle from Straight Ahead: Left 90 deg	60 deg	30 deg	0 deg	30 deg	60 deg	Right 90 deg
Above head	10.4	8.4	8.9	6.4	8.1	8.1	10.7
Shoulder height	9.4	8.6	7.9	5.33	7.9	8.1	9.1
Below waist	10.4	7.6	7.6		7.1	7.4	8.4

Subjects point at well-learned target positions without being able to see the targets. The targets were straight ahead at 30°, 60°, or 90° to the left or right. One horizontal row of targets was above head height, another was at shoulder height, and a third row was below waist level. The scores are the average error in centimeters from target center. (Based on research of Ref. 2 reported in Ref. 1)

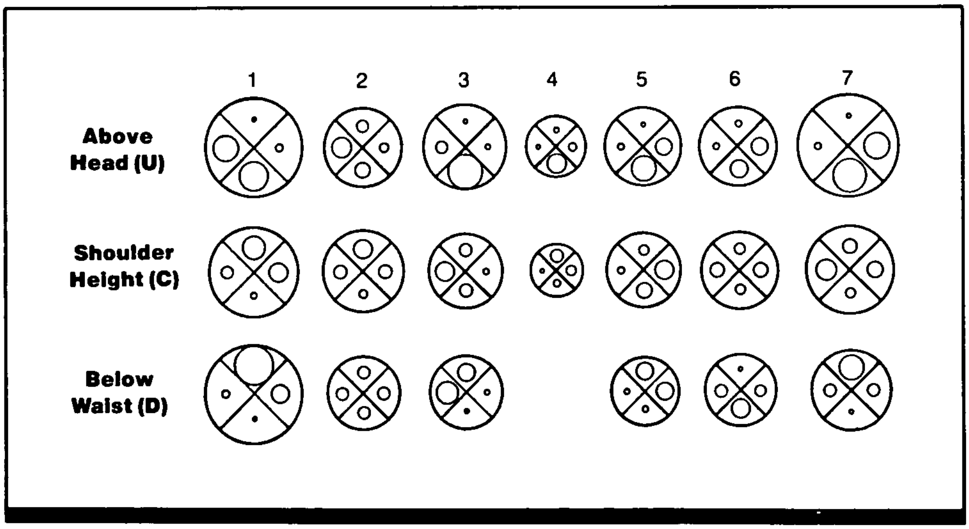

Figure 2. Direction of errors for each target represented by circle in each quadrant of target; circles are proportional in size to number of errors in that quadrant. (From Ref. 2)

9.209 Restricted Blind-Positioning: Effect of Distance and Direction

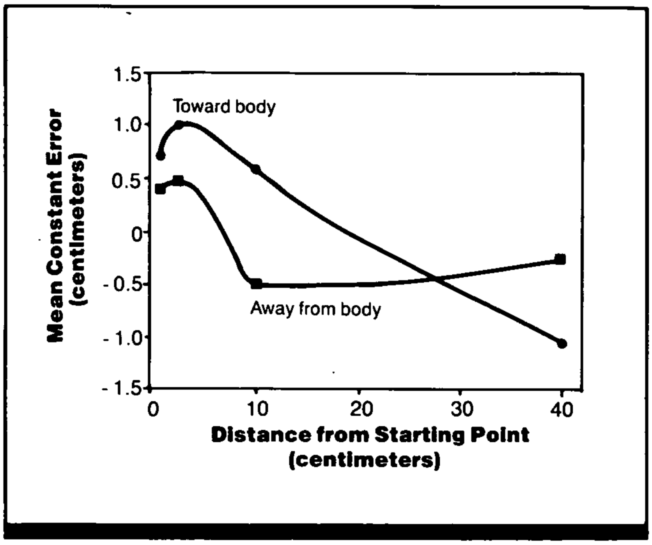

Figure 1. Mean error for restricted blind-positioning movements for different distances and directions of movement. (From Ref. 2, adapted from Ref. 1)

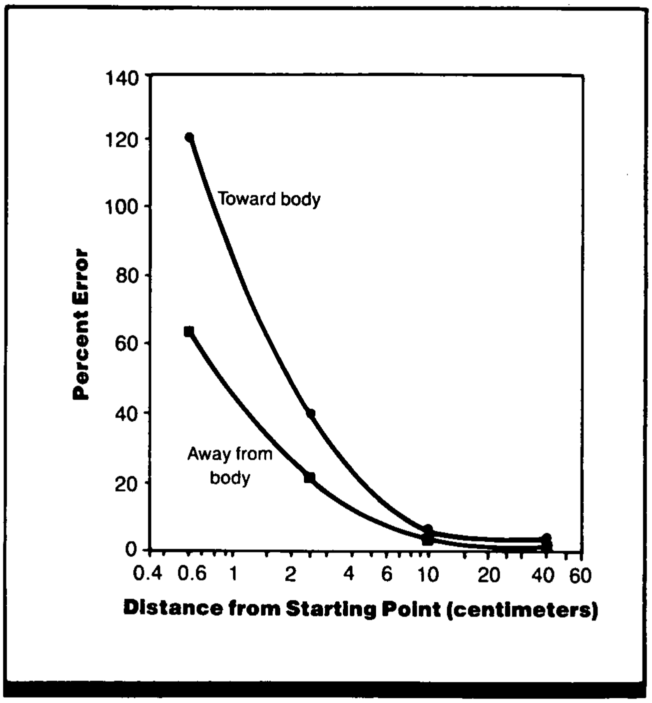

Figure 2. Percentage error of blind-positioning movements for different distances and directions. (From Ref. 2, adapted from Ref. 1)

Key Terms

Blind positioning; restricted positioning; visual feedback

General Description

When making restricted blind-positioning movements by sliding a lever or knob along a straight path, in the dark, short distances are overestimated and longer distances are underestimated. Movements away from the body are more accurate than those toward the body. Over the range of 0-40 cm, percent error is greatest at small values, diminishes rapidly through 10 cm, and then remains constant.

Applications

Designing control panels to minimize movement errors.

Methods

Test Conditions

- Subject shown beginning and target positions, then light extinguished while subject moved knob the instructed distance
- Subject moved knob (1) in horizontal plane, away from center of body, along line perpendicular to frontal plane of body; (2) as in (1), but toward center of body; (3) in horizontal plane, away from center of body, from point centered in front of body toward right; (4) as in (3) but from point at right toward center
- Knob to be moved 0.6, 2.5, 10, or 40 cm

Experimental Procedure

- Independent variables: movement distance; movement direction (away from or toward body); plane of movement (perpendicular to frontal plane of body or from point centered in front of body)
- Dependent variables: discrepancy between target position and actual location of knob, as indicated by mean error; percentage error (mean error divided by distance); and standard deviation of errors
- Subject's task: slide knob as close to target as possible
- Ten consecutive trials per subject for each distance-direction-plane-of-movement condition
- 48 subjects, tested at weekly intervals for different conditions to minimize practice effects

Experimental Results

- The errors of blind-positioning movements made along a line perpendicular to the frontal plane of the body are similar to errors of movement with respect to a point centered in front of the body.
- Subjects tend to overestimate short distances and underestimate long distances.
- Blind movements away from the body tend to be more accurate than movements toward the body.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

- The percentage error of blind movements (error divided by distance) is highest for short distances and does not vary much beyond 10 cm.
- Standard deviation of error increases with the distance. It is greater for movement away from, rather than toward, the body. Percentage variability (variability divided by distance), decreases with distance.
- The smallest errors and lowest variability of movements are for distance of 10-40 cm.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The tendency to overestimate small distances and underestimate long distances is similar to the range effect of another study (Ref. 3), which found that step inputs of random magnitudes elicited responses whose magnitudes tended toward the mean.

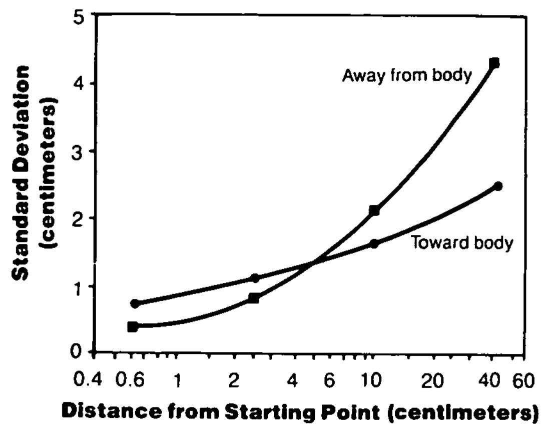

Figure 3. Standard deviation of blind-positioning movements of different distances and directions. (From Ref. 2, adapted from Ref. 1)

Key References

*1. Brown, J. S., Knauft, E. B., & Rosenbaum, G. (1947). The accuracy of positioning reactions as a function of their direction and extent. *American Journal of Psychology, 61*, 167-182.

2. Chapanis, A., Garner, W. R., & Morgan, C. T. (1949). *Applied experimental psychology*. New York: Wiley.

3. Searle, L. V., & Taylor, F. V. (1948). Studies of tracking behavior. I. Rate and time characteristics of simple corrective movements. *Journal of Experimental Psychology, 38*, 615-631.

Cross References

5.1107 Adaptation to prismatic displacement of the visual field: effect of feedback delay;

5.1108 Adaptation to prismatic displacement of the visual field: effect of feedback conditions;

9.204 Blind positioning: effect of prior target exposure;

9.206 Reaching hand movements; effect of varying visual feedback;

9.210 Time and accuracy of fast control movements

9.210 Time and Accuracy of Fast Control Movements

Key Terms

Fitts' Law; Schmidt's Law; visual feedback

General Description

Fitts' Law (CRef. 9.201), which describes movement time (*MT*) as a constant for any given ratio of distance to target width (or accuracy), applies to movements that are slow enough to allow aim correction by visual feedback (CRef. 9.206). However, faster movements require greater starting and stopping forces; this increase in force leads to a decrease in accuracy, which is determined by variability in the preprogrammed muscular impulses (rather than by error corrections due to feedback). The accuracy of briefer movements is dependent on the speed of movement and can be described by a variant of Fitts' Law, called Schmidt's Law:

$$W_e = a + b\,(D/MT)$$

where a and b are constants, D is movement distance, and MT is movement time. The result of the computation, W_e, is the standard deviation of endpoint dispersion and is known as the effective target width.

Schmidt's Law provides a good description of accuracy for movements lasting from 140-200 msec over distances of up to 30 cm; it describes errors which are parallel or perpendicular to the line of travel; the constants a and b differ in those two cases (Fig. 1). However, Schmidt's Law breaks down when movements involve forces that exceed 60-70% of a subject's capability. At near-maximal force levels, spatial accuracy improves in the direction perpendicular to the line of movement, and variability of the force generated decreases for both static and dynamic contractions (Fig. 3), even though at lower force levels the variability is a linear function of the force generated (Fig. 2).

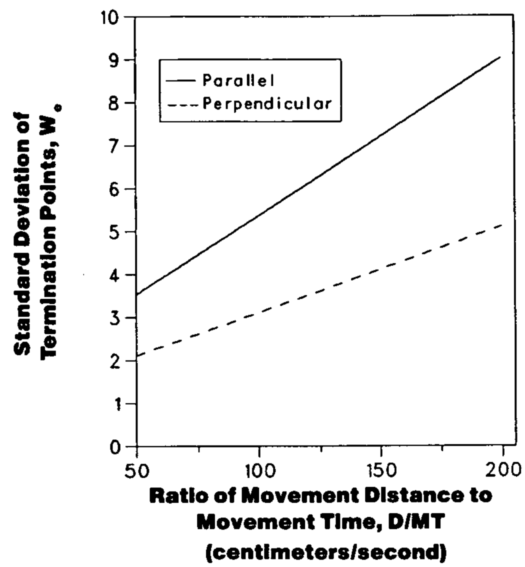

Figure 1. Schmidt's Law relating accuracy (measured in terms of standard deviations of termination points of movement) and the ratio of movement distance to movement time. The solid line is for errors perpendicular to the line of movement and the dashed line is for errors parallel to the line of movement. (From *Handbook of perception and human performance*, based on Ref. 2)

Methods (Ref. 3)

Test Conditions

For static contractions

- Seated subject faced an oscilloscope displaying horizontal target lines 5.7, 7.1, 8.5, 9.9, or 11.3 cm from the bottom (zero) position; target lines represented forces of 59.1, 115.9, 170.2, 226.2, and 281.2 N
- Force measured via lever with vertical handle connected by cable to a strain gauge; subject grasped handle with right hand so that elbow was at right angle in horizontal plane; isometric contractions by subject determined distance a dot moved from bottom of screen toward the target line; contractions paced by metronome set at one click per sec

For dynamic contractions

- Subject rotated lever (52.07 cm long x 4.45 cm wide) in the horizontal plane (via elbow flexion and extension); a D-shaped handle bolted to the lever via a strain gauge 33.02 cm from the pivot measured force; masses of 26, 52, 78, 92, or 130 N added to lever to change required force to approximately 30, 45, 56, 68, 71, or 80% of the subject's static strength

Experimental Procedure

- Independent variables: positions of target lines for static force, amount of load for dynamic force
- Dependent variable: amount of force applied by subject
- Subject's task: for static task, pull handle with appropriate force to move dot up to designated target line; for dynamic task, move handle 30 deg in 150 msec
- For static task, 5 right-handed male students (ages 19-21), with some practice; for dynamic task, 6 right-handed female students (ages 20-24), with some practice (subjects had to be able to produce more than 125 N of static elbow-flexion strength)

Experimental Results

- The results shown in Figs. 1 and 2 are included as background for the reported work that demonstrates the breakdown of Schmidt's Law (Fig. 1) at forces near subjects' maximal force capacity. Details of methods and procedures are available in Refs. 1, 2.
- Force variability is a linear function of required force at levels <60-70% of subjects' force capacity (Fig. 2). However, when subjects' maximal force levels are approached, the linear relationship breaks down; force variability peaks and then declines (Fig. 3).
- The location of the breakdowns of the linear functions for static and dynamic force is similar to the location of the breakdown in the function for accuracy; accuracy is inversely related to speed of movement and increasing distance (Schmidt's Law), but the linear relationship also breaks down at ~60-70% of the subjects' maximal force capacity.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Variability

No information on variability was given for these experiments, but the correlations between force and force variability for individual subjects in earlier experiments in the series ranged from 0.84-0.99.

Repeatability/Comparison with Other Studies

The experiment requiring dynamic force was replicated with larger masses matched to each subject's maximum contractual strength. The linear relationship between force and force variability broke down at 55-60% of maximum strength, with relatively large decreases in variability at greater masses.

Key References

1. Schmidt, R. A., Zelaznik, H. N., & Frank, J. S. (1978). Sources of inaccuracy in rapid movement. In G. E. Stelmach (Ed.), *Information processing in motor control and learning*. New York: Academic Press.

2. Schmidt, R. A., Zelaznik, H. N., Hawkins, B., Frank, J. S., & Quinn, J. T., Jr. (1979). Motor output variability: A theory for the accuracy of rapid motor acts. *Psychological Review, 86*, 415-451.

*3. Sherwood, D. E., & Schmidt, R. A. (1980). The relationship between force and force variability in minimal and near-maximal static and dynamic contractions. *Journal of Motor Behavior, 12*, 75-89.

Cross References

9.201 Fitts' Law: movement time as a function of distance and accuracy;

9.202 One- versus two-handed reaching: effect of target distance and width;

9.204 Blind positioning: effect of prior target exposure;

9.206 Reaching hand movements: effect of varying visual feedback;

9.207 Control movement times under water and on land;

Handbook of perception and human performance, Ch. 30, Sect. 2.3

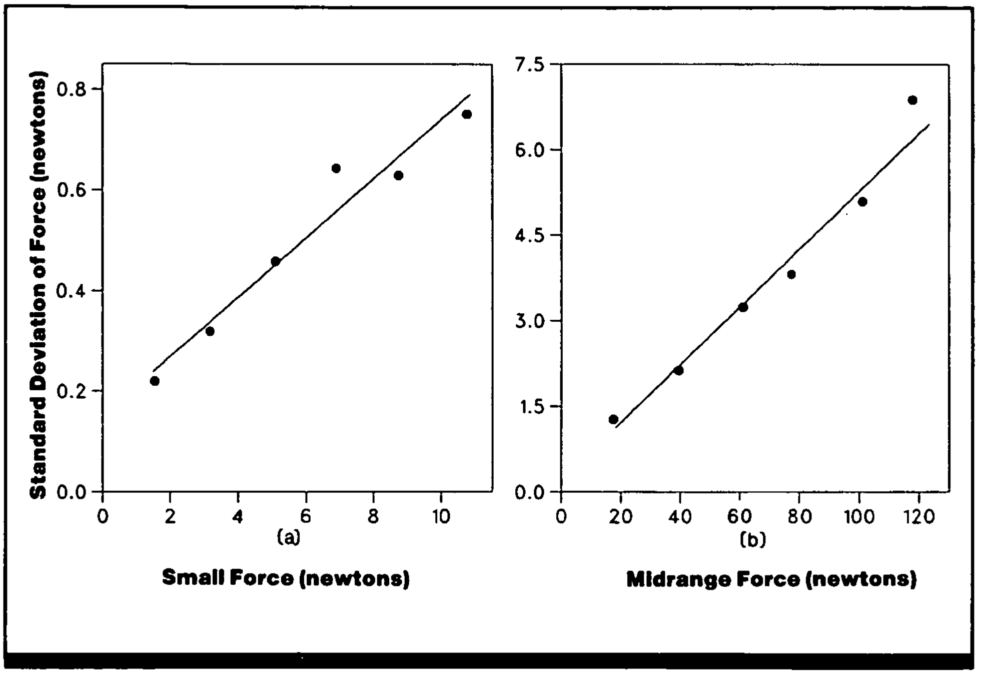

Figure 2. Standard deviations as a function of absolute amount of force generated by subjects for (a) small and (b) midrange forces. (From *Handbook of perception and human performance*, based on Ref. 2)

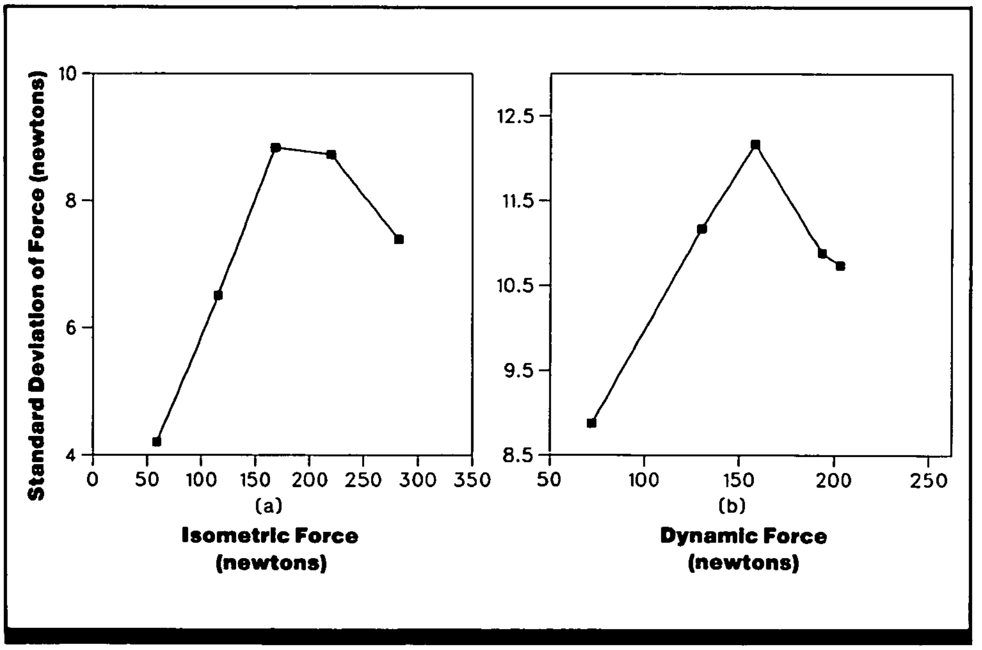

Figure 3. Standard deviations as a function of absolute amount of force generated by subjects for (a) isometric and (b) dynamic near-maximal forces. (From *Handbook of perception and human performance*, based on Ref. 3)

9.301 Maximum Tapping Speed: Effect of Age and Sex

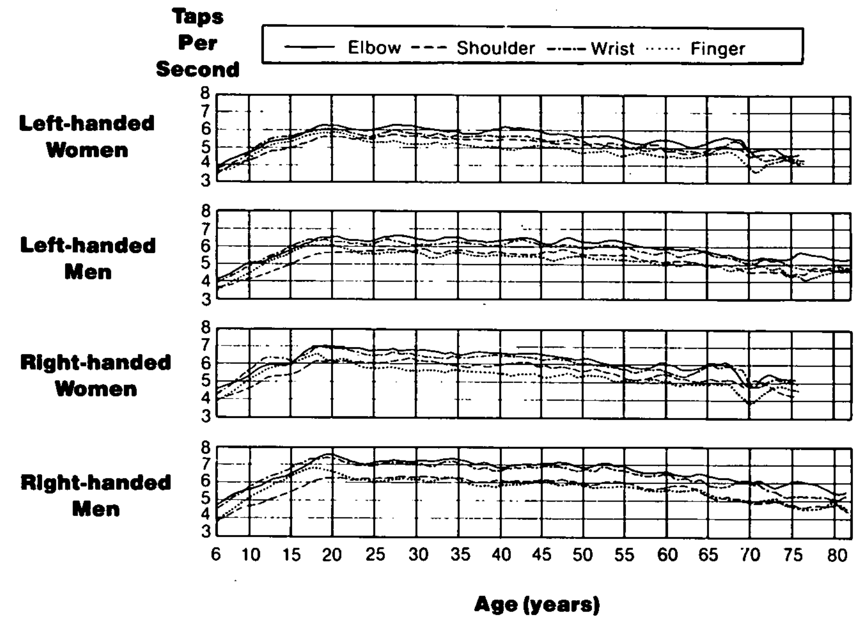

Figure 1. Mean number of maximum taps per sec for different body parts as a function of age for left-handed and right-handed men and women. (From Ref. 2, based on Ref. 4)

Key Terms

Movement time; shoulder joint; tapping; telegraph key; wrist

General Description

Some motor tasks involve repetitive movement of a set of articulators (jointed body parts, such as fingers). The maximum rate of repetition, as measured by the mean number of taps per sec, increases up to ~age 18 and depending on the specific articulator, may decrease slightly or remain constant until about age 50 (Fig. 1). In general, articulators on the right side tap faster than those on the left, and males tend to be slightly faster than females. Tapping by moving the elbow is fastest, followed by the wrist, shoulder, and finger (shown for ages 25-48 in Table 1).

Methods

Test Conditions

- Subjects tapped on standard Morse telegraph key with number of taps recorded on a clock face connected to the key
- For shoulder movement, the forearm was held at right angles to the upper arm and the back of the elbow was held above the button of the key; the upper arm was moved up and down as rapidly as possible in a plane nearly parallel with the vertical plane of the body
- For elbow movement, the elbow rested on a table with forearm held at right angle to the upper arm; the key was struck with the inside of the forearm just behind the wrist
- For wrist movement, the elbow rested on the table; an iron clamp with padded jaws loosely held the forearm just behind the wrist joint; the key was struck with palm of the hand
- For finger movement, palm of the hand was held with moderate firmness by a clamp at an angle of ~135 deg to the forearm; the finger in position was then nearly parallel with the forearm to avoid sympathetic movements of the wrist

Experimental Procedure

- Independent variables: age (6-86 yrs), sex, right of left side or body, and articulator (finger, wrist, elbow, or shoulder)
- Dependent variable: number of taps per sec
- Subject's task: tap key as quickly as possible using the designated movement
- 2000-3000 subjects, males and females

Experimental Results

- Mean tapping rate increases until age 18 and then remains constant until about age 50 when it begins to decrease.
- Articulators on the right side of the body tap slightly faster than articulators on the left.
- Mean tapping rate for men is slightly faster than the mean rate for women.
- Mean tapping rate is fastest for the elbow, followed by the wrist, then the shoulder, and finally the finger.

Variability

Within-subject variability is small, ranging from 0.85-1.4 taps per 5 sec.

Repeatability/Comparison with Other Studies

In a tapping task where subjects alternated between targets, movement time did not change much from ages 20-60; from 60-79, changes in target distance rather than target width affected movement time (Ref. 5). A similar pattern of tapping rate was found with college students (shoulder and elbow were faster than finger, thumb, and foot); a slightly lower tapping rate (e.g., 6 taps per sec for elbow) was probably due to procedural differences (Ref. 3, CRef. 9.302).

Constraints

- In this study, only the first tap for each trial was a response to an experimenter-presented stimulus. Thus it is not clear how these data would generalize to situations in which each movement (tap) is a response to a separate stimulus (e.g., as in typing).

Key References

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2. Keele. S. W. (1986). Motor control. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance.* New York: Wiley.

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Cross References

9.201 Fitts' Law: movement time as a function of distance and accuracy;

9.302 Tapping rate, typing speed and handwriting speed;

9.303 Typing speed and accuracy;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.410 Keyboards and keysets: effects of key size, force, displacement, and feedback on keying performance

Table 1. Mean number of taps per sec for different effectors (subjects aged 25-48). (From Ref. 2, based on Ref. 4)

		Finger	Wrist	Elbow	Shoulder
Men	Right	6.00	6.93	7.08	6.12
	Left	5.55	6.23	6.43	5.66
Women	Right	5.58	6.48	6.67	6.05
	Left	5.23	5.78	6.10	5.63

9.302 Tapping Rate, Typing Speed, and Handwriting Speed

Table 1. Correlations between maximum tapping rates for different muscle systems. (From Ref. 3)

	Finger	Thumb	Wrist	Arm	Foot
Finger	**0.86**	0.80	0.84	0.69	0.75
Thumb	0.73	**0.95**	0.98	0.79	0.68
Wrist	0.70	0.85	**0.80**	1.0	0.74
Arm	0.59	0.72	0.91	**0.86**	0.69
Foot	0.67	0.59	0.64	0.61	**0.92**

Key Terms

Foot; handwriting; movement time; tapping; telegraph key; wrist

General Description

There are large differences between people in performance of highly skilled tasks such as handwriting and typing. The maximum rate at which an individual taps with one articulator (a jointed body part such as a finger) is highly correlated with maximum rates for other articulators (e.g., wrist, arm, and foot). Tapping speed also correlates with handwriting speed and correlations might be even higher if a speed/legibility criterion were developed.

The length of the interval between two key presses by the same finger is consistent with maximum tapping speed for professional typists; however, tapping speed does not increase with typing practice. This suggests that maximum tapping rate constrains an individual's typing speed.

Methods

Test Conditions

- Subject repetitively tapped with forefinger, thumb, wrist, elbow, or ankle; four 7-sec trials for each articulator
- Subject wrote a sentence several times at own normal writing speed, on lined paper or on a blackboard, using arm movements

Experimental Procedure

- Independent variables: specific articulator, type of handwriting
- Dependent variables: movement time (MT) as mean taps per second and msec per tap, time to write sentences
- Subject's task: tap as rapidly as possible using the designated articulator; write sentences at normal handwriting speed
- 15 college-age subjects

Experimental Results

- Within-subject correlations for maximum tapping rates for different articulators range from 0.59-0.91 ($p < 0.01$) when uncorrected for attenuation and 0.68-1.00 ($p < 0.01$) when corrected for attenuation (i.e., as if reliability were perfect). Thus tapping rates are correlated for different muscle systems, including foot and upper-limb articulators.
- Mean tapping speed (across all articulators) is correlated 0.63 with handwriting speed on paper; for individual articulators, specific correlation coefficients are finger (0.54), thumb (0.41), wrist (0.56), arm (0.52), and foot (0.64).
- Blackboard writing speed does not correlate with maximum tapping speed for any articulator.
- Maximum speed for wrist and arm is faster (6 taps/sec) than for finger, thumb, and foot (5 taps/sec).

Variability

The correlations on the diagonal in Table 1 (shown in boldface) are indices of reliability and thus serve as limitations for the interarticulator correlations.

Repeatability/Comparison with Other Studies

For six professional typists, maximum tapping speed correlated with interstroke intervals for repetitions of the same finger (Ref. 2), with the interval ranging from 164-225 msec (the mean for this experiment was 201 msec/tap). World typing champions tapped ~25-33% faster than matched controls (Ref. 1). Tapping speed and typing speed were not correlated for high school students (Ref. 4), suggesting that other factors limit speed for subjects or tasks that are not highly practiced.

Constraints

- The mean 5-6 taps per sec found here is slightly lower than means of 6-7 shown in a study (CRef. 9.301) involving a much larger number of subjects.
- Within-subject correlations of tapping rates between different articulators for the same subject do not mean that people who show high-frequency tapping are quicker on nonrepetitive tasks such as reaction time.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

9.301 Maximum tapping speed: effect of age and sex;

9.303 Typing speed and accuracy;

12.406 Numeric keyset arrangements: effects on speed and accuracy of data entry;

12.407 Conventional versus membrane keyboards;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.410 Keyboards and keysets: effects of key size, force, displacement, and feedback on keying performance;

12.415 Selection of data entry devices: ten-button keyset, matrix keyboard, vertical levers, and rotary selectors

9.303 Typing Speed and Accuracy

Table 1. Mean time per typed symbol (letters, spaces, and punctuation) in msec and distribution of errors for each of the 10 passages. (From Ref. 3)

		Prose Word Order				Random Letter Strings	
Passage Presentation Order	**Passage Type**	**Normal**	**Random**	**String Length**	**Non-Word Syllables**	**Letters Distributed as in Text**	**All Letters Equiprobable**
Random	Easy	151	152	Fixed (6 letters)	195	239	329
	Technical	157	157	Variable	197	239	332
Most-structured to least-structured	Easy	166	163	Fixed (6 letters)	222	265	357
	Technical	171	167	Variable	217	268	359
	Total number of errors	63	65		97	130	230

Key Terms

Motor coordination; motor skills; speed-accuracy tradeoffs; typing

General Description

Meaningful words and text are typed faster and more accurately than pronounceable non-word syllables (e.g., *throx*); sequences of random letters lead to poorest performance. While motor skills are being learned, movements are separated by a relatively long interval filled by an evaluation of the previous movement that determines the next one. With practice, a sequence of movements coalesces into a single pattern that is initiated as a whole in response to a single stimulus. When information is meaningfully structured (e.g., into words), a sequence of responses is faster.

Applications

For tasks in which a subject transcribes commands or instructions, the use of sequences of meaningless symbols (e.g., unfamiliar acronyms) may reduce the quality of performance.

Methods

Test Conditions

- Ten sets of printed text divided as follows: four prose passages (one technical, one non-technical), each in normal or random word order; two versions of technical passage with spaces rearranged to eliminate words but not syllables—one version with fixed string lengths of six letters, one with varying string lengths distributed as in normal text; two versions of technical passage with words and syllables removed, rearranged into fixed-length or variable-length letter strings; two letter strings in which each letter is equally likely to appear, organized into fixed-length letter strings or strings of varying lengths
- Passages ~250 letters long, printed in lower case, 10 point type, one and one-half spaces between lines
- Passages in full view of subject
- Time between passage presentations not specified
- For random-order condition, passages typed in unique random order by each subject; for fixed-order condition, passages typed in invariant order from most-structured to most-random

Experimental Procedure

- Independent variables: degree of passage structure, passage presentation order
- Dependent variables: mean time per typed symbol, number of typing errors (defined as any departure from the text)
- Subject's task: type each passage as quickly and accurately as possible without use of capitalization
- Auditory signal started timer and initiated trial; no error correction or stopping allowed
- 20 adult subjects (10 per group), extensive touch-typing experience (defined as ≤2-1/2% error rate on passages); subjects used own typewriters (some mechanical and some electrical)

Experimental Results

- Normally ordered prose and randomly ordered prose are typed with equivalent speed and accuracy (confirmed in a control study using other passages); performance declines dramatically as additional structure is removed from passages.
- Mean response times are longer for pronounceable non-word syllables than for actual words ($p < 0.001$).
- Mean response times are longer for random-letter strings in which all letters are equally likely to occur than for strings with letters distributed as in text ($p < 0.001$).

Variability

Analysis of variance and post-hoc Scheffe tests were used.

Repeatability/Comparison with Other Studies

Perceptual advantages of words and pronounceable nonwords over unstructured letter strings are well established (Refs. 2, 4).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Difference in response times between the group with random passage presentation order and the group with most-structured to least-structured presentation order could not be statistically analyzed because of non-random assignment of subjects to the two groups.

• Values obtained may not hold for untrained or less experienced subjects (Ref. 1).

• Subjects performed the task with familiar equipment. Novel apparatus may diminish the effect.

• Error rates are generally influenced by the speed requirements of the response (the speed-accuracy tradeoff) (CRef. 9.108).

Key References

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Cross References

9.105 Speed-accuracy tradeoffs;

9.108 Factor affecting simple reaction time;

9.119 Choice reaction time: effects of practice;

9.121 Interaction among multiple stimuli and responses;

9.302 Tapping rate, typing speed, and handwriting speed;

12.407 Conventional versus membrane keyboards;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.410 Keyboards and keysets: effects of key size, force, displacement, and feedback on keying performance

9.304 Effect of Auditory and Visual Feedback on Performance of Coordinated Movements

Key Terms

Auditory feedback; delayed feedback; feedback; foot switch; tapping; visual feedback

General Description

Tasks such as tapping a finger or speaking usually produce immediate auditory feedback. When the expected feedback following a tapping response is consistently delayed, individuals notice the aberration and compensate. When feedback is occasionally, very briefly delayed (e.g., 20 msec), subjects may not report an awareness of the perturbations, but their pattern of responding changes, with one or two lengthened interresponse intervals following the presentation of delayed feedback. Advanced feedback does not produce such an effect. The increase in the interresponse interval is never as long as the delay suggesting that feedback may alter timing but is not the sole source of the timing.

Methods

Test Conditions

- Binaural presentation by headphones of stimulus presentations and auditory feedback; stimulus presentations were sixteen 10-msec, 1900-Hz tones at 80 dB (re threshold); auditory feedback was 5 msec, 1000 Hz tone
- Stimuli were presented every 350, 500, or 650 msec
- Response-feedback interval was 15 or 25 msec except when delayed or advanced (perturbation)
- Subject pressed floor switch and heard 400-msec warning signal that preceded the first stimulus by 1600 msec, then tapped in synchrony with 16 stimulus presentations with feedback, and then continued with another 20 responses at the established rate without stimulus presentations but with feedback (termination signal indicated twentieth continuation response)
- A 10 msec advance or a 20 or 50 msec delay of feedback (perturbation) occurred after either the ninth, tenth, eleventh, or twelfth continuation response

Experimental Procedure

- Within-subjects design
- Independent variables: interstimulus interval (350, 500, or 600 msec), response-feedback interval (15 or 25 msec), advance or delay of feedback (perturbation), length of perturbation (10, 20, or 50 msec), continuation response number after which advance or delay presented (9-12)
- Dependent variable: changes in interresponse intervals following feedback perturbation, measured by subtracting the mean interval for the five intervals preceding the perturbation from the interval for the response being analyzed
- Subject's task: synchronize taps of the index finger to the 16 stimulus presentations and then continue tapping with the same interresponse interval for 20 more responses
- Monetary payoffs designed to keep the mean interresponse interval within 5 msec of the interstimulus interval and the range of the interresponse intervals within ±40 msec of the interstimulus interval
- Visual feedback included value of interstimulus interval, mean interresponse interval for the 20 continuation responses, the largest and smallest values for the continuation responses, and the amount of monetary gain for the trial
- Tones were presented against a background of 70 dB (re threshold) white noise
- 3 right-handed female subjects with extensive practice

Experimental Results

- The interresponse intervals approximately reflect the length of the interstimulus intervals (within ~10 msec).
- The variance of the interresponse interval (I) with the

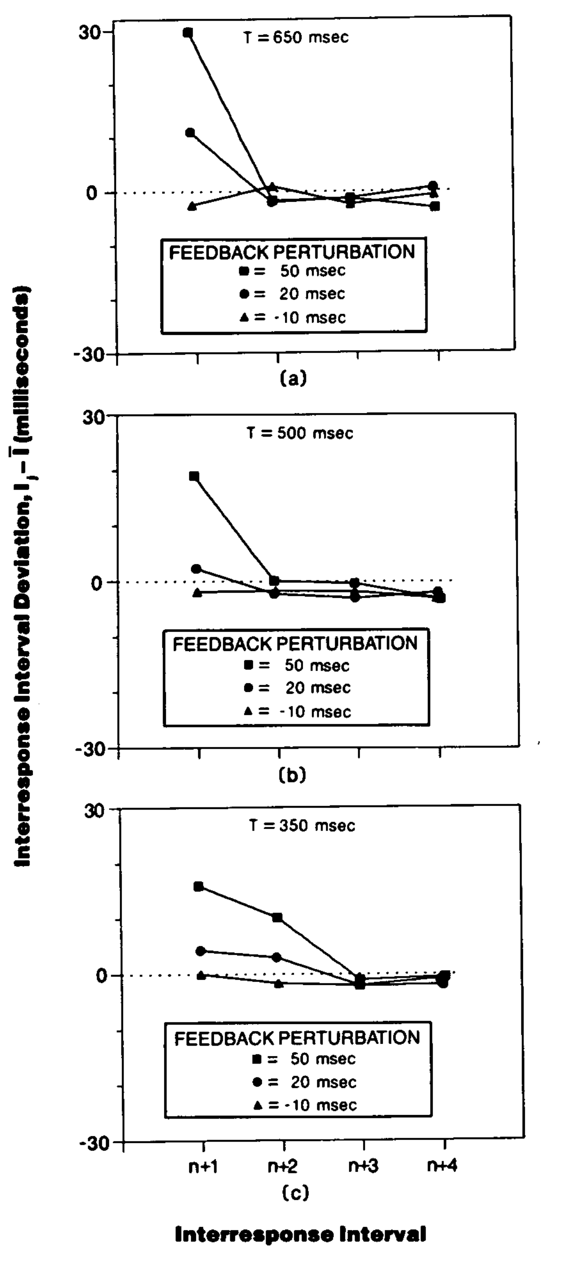

Figure 1. Deviations of interresponse intervals from the mean as a function of the number of trials after a perturbation in the timing of auditory feedback. The value of T is the interstimulus interval for the equally spaced stimuli. A negative change decreased the feedback interval and a positive change increased the feedback interval. (From Ref. 2)

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perturbation of feedback (I_n) and the covariance of I_n, I_{n-1}, increase with the duration of the interstimulus intervals.

- A delay in feedback is reflected in a lengthened subsequent interresponse interval of (I_{n+1}). A 50 msec delay leads to a longer interresponse time than a 20 msec delay. Shortening the feedback interval by 10 msec produces no effect. A smaller but similar effect is found for (I_{n+2}).

Variability

Although significant interaction terms in the completely fixed-effect analysis of variance indicated there were individual differences among subjects, the data pattern for each subject corresponded to the pattern of the average data.

Repeatability/Comparison with Other Studies

Other evidence also indicates that delayed auditory feedback has an effect on repetitive equal-interval tapping responses (Ref. 1).

Constraints

- Only 3 well-practiced female subjects were studied; thus the generality of these findings has not been established.

Key References

1. Chase, R. A., Rapin, I., Gilden, L., Sutton, S., & Guilfoyle, G. (1961). Studies on sensory feedback. II: Sensory feedback influences on keytapping motor tasks. *Quarterly Journal of Experimental Psychology, 13*, 153-167.

*2. Wing, A. M. (1977). Perturbations of auditory feedback delay and the timing of movement. *Journal of Experimental Psychology: Human Perception and Performance, 3*, 175-186.

Cross References

5.113 Prismatic displacement of the visual field: visual and auditory judgments of straight ahead;

5.1127 Adaptation to rearrangement of auditory space;

9.206 Reaching hand movements: effect of varying visual feedback;

9.209 Restricted blind-positioning: effects of distance and direction;

9.305 Coordination of hand movements on timed tasks;

9.307 Hand and voice coordination;

9.404 Effect of knowledge of results on motor learning;

9.501 Tactile and visual tracking: effects of error feedback;

Handbook of perception and human performance, Ch. 30, Sect. 4.4

9.305 Coordination of Hand Movements on Timed Tasks

Key Terms

Coordinated hand movement; simultaneous response; staggered response; synchronous response; telegraph key

General Description

When responses involve both the right and left hands, complex responses can be generated in parallel with little interference if the two responses are temporally compatible (i.e., the repetitions of the two responses are based on the same time frame). However, responses that are temporally incompatible interfere with each other, even when both responses are relatively simple. Comparisons of simultaneous responses (same period, same phase), staggered responses (same period, different phase), and rhythmically related responses (e.g., the period for one hand is half that for the other hand) indicate that the best performance is achieved when the movement of one hand does not overlap the movement of the other hand (staggered responses).

Methods

Test Conditions

- Two telegraph keys, one to subject's left and one to the right, separated by 68 cm; keys pressed by left and right index fingers, respectively
- For all conditions, left hand pressed and released a telegraph key in synchrony with onset and offset of a 2900-Hz tone presented to the left ear
- Different right-hand tasks: (a) identical, in which right-hand key presses were synchronized with a right-ear 4500-Hz tone that was in phase with the tone to the left ear; (b) skip, in which the tone to the right ear occurred only for every other onset of the tone to the left ear; (c) unsynchronized, in which pattern of right-ear tone was either 2 sec off and 0.6 sec on or 1.6 sec off and 0.6 sec on; and (d) no tone to the right ear and subjects instructed to press the telegraph key repeatedly as quickly as possible with the right hand
- Each trial had 10 sec of unmeasured performance, 20 sec of measured performance, and then 5-10 sec of unmeasured performance; intertrial interval of ~10 sec; trials blocked by condition

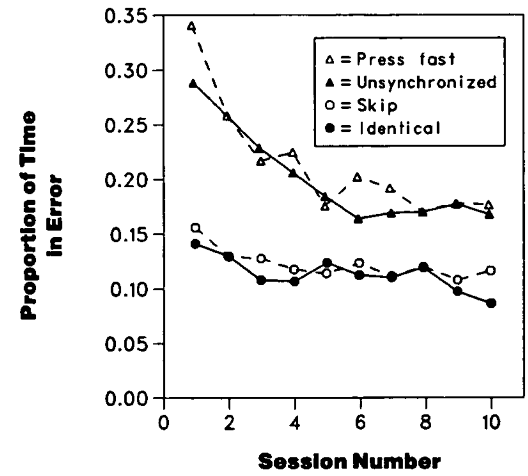

Figure 1. Left-hand performance error as a function of the amount of practice and the task of the right hand (identified in the figure legend). (From Ref. 1)

Experimental Procedure

- Within-subjects design
- Independent variables: task performed by right hand, session number
- Dependent variable: percent error for left and right hands
- Subject's task: press telegraph keys with right and left index fingers in patterns indicated by experimenter's instructions
- 8 right-hand college students with some practice

Experimental Results

- Left-hand performance for each of the temporally compatible conditions is better than performance for each of the temporally incompatible conditions ($p < 0.25$). Performance on the two temporally compatible conditions does not differ, nor does performance on the two temporally incompatible conditions.
- Left-hand performance improves over the first five days, especially for the temporally incompatible conditions. Beginning with the sixth day, performance does not improve for any condition. No data are given for improvement of right-hand performance.
- Response interference can be either right with left (as above) or left with right; right-hand performance was better for the skip condition (1:2 ratio of left-to-right responses) than for the unsynchronized condition ($p < 0.001$) at all levels of practice.

Variability

An analysis of variance was used; no mean square errors were reported.

Repeatability/Comparison with Other Studies

A 1:2 ratio effect has been reported for single-handed tapping of rhythmic intervals. There is a tendency for both hands to use the same time frame even when optimal performance on reaching tasks would dictate different speeds (CRef. 9.202). The same principle of temporal compatibility has been reported for hand/voice coordination (CRef. 9.307). This study included other experiments that yielded similar results. In the final experiment of the study, same-period, same-phase conditions were compared with a same-period, different-phase condition and a different-period, different-phase condition. The best performance was obtained when the same period was used with phase displacement such that the movements of the hands did not overlap (Ref. 1).

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Constraints

- It is not clear the extent to which various rhythmic periodicities are easy to accurately reproduce. Only the 2:1 harmonic relationship was considered, and in the final experiment the no-overlap phase shift combined a 0.6 sec right-hand press, 0.6 sec with no press, a 0.6 sec left-hand press, and 0.6 sec with no press, so that intervals were the same.

Key References

*1. Klapp, S. T. (1979). Doing two things at once: The role of temporal compatibility. *Memory and Cognition, 7*, 375-381.

2. Yamanishi, J., Kawato, M., & Suzuki, R. (1980). Two coupled oscillators as a model for the coordinated finger tapping by both hands. *Biological Cybernetics*, 37, 219-225.

Cross References

9.121 Interaction among multiple stimuli and responses;

9.122 Interference between concurrent tasks: effect of response mode similarity;

9.202 One- versus two-handed reaching: effects of target distance and width;

9.307 hand and voice coordination;

Handbook of perception and human performance, Ch. 30, Sec. 3.3

9.306 Step Cycle Times for Walking and Running

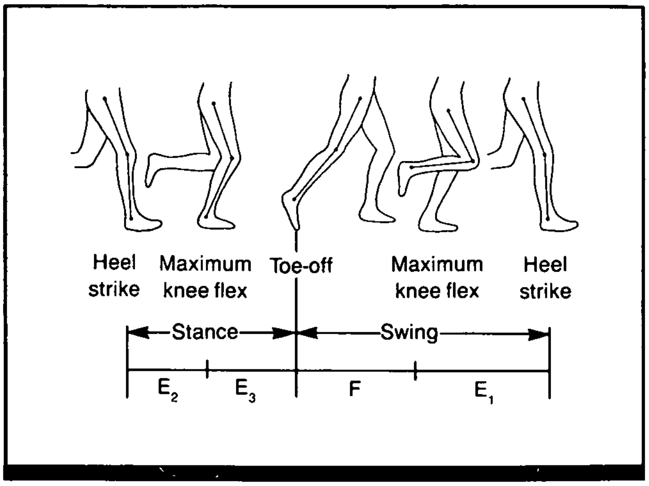

Figure 1. Four phases of Phillippson step cycle for walking and running. (From Ref. 3)

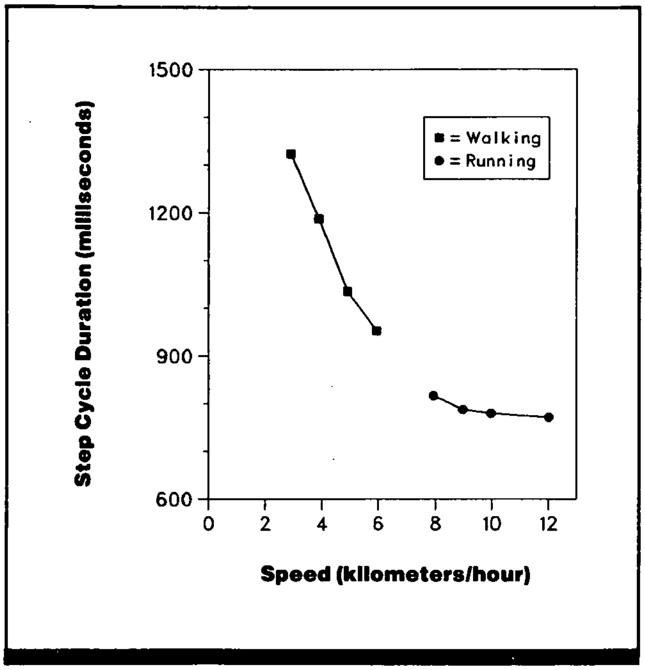

Figure 2. Step-cycle duration as a function of speed for walking and running. (From Ref. 3)

Key Terms

Gait; knee flex; locomotion; movement time; running; step cycle times; walking

General Description

The series of leg movements involved in walking and running can be analyzed in terms of a step cycle having four phases (Fig. 1): E_2 and E_3 constitute the stance portion of the cycle and F and E_1 are the swing portion. In walking, the duration of the step cycle decreases as walking speed increases (Fig. 2), indicating that speed is achieved by an increase in step frequency. The relative length of the step cycle's phases remains the same even with a two-fold increase in walking speed (Fig. 3).

In running, the duration of the step cycle only slightly decreases with increases in running speed (Fig. 2), indicating that speed is achieved by an increase in stride length. The relative length of the step cycle's phases for running remains similar even with a 1.5-fold increase in speed (Fig. 3).

The time spent in each phase for running is very different from the relative times for walking. Changing the gait from walking to running brings about changes in the relative timing of the step phases, but the relative timing of the phases remains fairly constant within each gait with increases in speed.

Methods

Test Conditions

- Subjects walked or ran on a treadmill at speeds increasing for 3-12 km/hr
- Circular markers on legs (as shown in Fig. 1) were filmed by motor-driven 16-mm camera with a 25-mm lens, positioned 8-m orthogonal to longitudinal axis of treadmill; 50 frames/sec camera speed, 30 deg shutter angle, 0.67 msec exposure time; filming began 150 sec after each speed change and lasted 30 sec
- Subject listened to white noise over headphones and looked at reference target at eye level on wall 3 m away

Experimental Procedure

- Independent variables: gait (walking or running), speed (7 km/hr not analyzed because 2 subjects walked and 3 subjects ran at that speed), phase of step cycle
- Dependent variable: length of time spent in each phase of cycle (mean of two successive step cycles for each speed)
- Subject's task: to walk or run on a treadmill
- 5 male experienced distance runners who were familiar with running on a treadmill, with some practice at each treadmill speed (age = 27.4 ± 6.1 yrs, height = 1.83 ± 0.09 m, and mass = 70.6 ± 5.8 kg)

Experimental Results

- The relative timing of the phases remains fairly constant within gait.
- There are significant changes in relative timing of the phases as the gait changes from walking to running: a larger proportion of the time is spent in the swing portion of the cycle, and the proportion for the stance portion decreases because the E_3 proportion decreases.

- There are large decreases in the absolute times of the phases of the step cycle as speed increases for either walking or running, and the duration of the stance portion of the cycle decreases more with speed than does the duration of the swing portion.

Variability

A multivariate analysis of variance was used; error values were not reported.

Repeatability/Comparison with Other Studies

The cycle duration for three long jumpers as they approached the jump changed only ~10% from the first to the fifteenth stride (Ref. 1). The invariance of proportional timing has been found for handwriting (Ref. 2), serial key-pressing (Ref. 4), and typing (Ref. 5).

Constraints

- Stride frequency in human running is about one-third that of tapping frequency of other articulators. Stride frequency may be partially dependent on mechanical factors related to the mass of the organism, whereas frequencies of finger, wrist, forearm, upper arm, and foot may be weakly related to length and mass of the articulator.

Key References

1. Lee, D. N., Lishman, J. R., & Thomson, J. A. (1982). Regulation of gait in long jumping. *Journal of Experimental Psychology: Human Perception and Performance, 8*, 448-459.

2. Merton, P. A. (1972). How we control the contraction of our muscles. *Scientific American, 226*, 30-37.

*3. Shapiro, D. C., Zernicke, R. F., Gregor, R. J., & Diestel, J. D. (1981). Evidence for generalized motor programs using gait pattern analysis. *Journal of Motor Behavior, 13*, 33-47.

4. Summers, J. J. (1975). The role of timing in motor program representation. *Journal of Motor Behavior, 7*, 229-242.

5. Terzuolo, C. A., & Viviani, P. (1979). The central representation of learned motor patterns. In R. E. Talbott & D. R. Humphrey (Eds.), *Posture and movement*. New York: Raven.

Cross References

3.303 Factors affecting sense of position and movement of body parts;

Handbook of perception and human performance, Ch. 30, Sect. 3.1

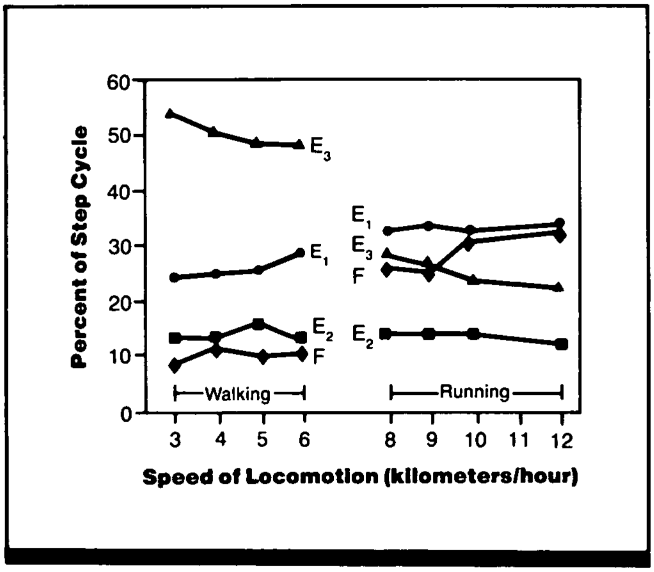

Figure 3. Relative time spent in each phase of step cycle in terms of percent of total time for step cycle as a function of speed of walking and running. (From Ref. 3)

9.307 Hand and Voice Coordination

Key Terms

Coordinated hand movement; manual response; synchronous response; telegraph key; voice coordination; word articulation

General Description

Word articulation (e.g., pronunciation of the syllable "la"), whether voiced or silent, interferes with a manual task if the periodicity of the articulation is different from the periodicity of the manual task. Simultaneous articulation and a manual response having the same periodicity can be performed about as well as the manual task alone.

Methods

Test Conditions

- Manual response: to press a telegraph key with the fingers of the right hand so that key was down while a 300-Hz tone sounded in the right ear for 300 msec and was up while the tone was off for the remainder of a 1500-msec period
- A 3000-Hz alarm sounded in the left ear if the key was not depressed during the central 100 msec of the 300-msec tone or if the key was depressed during a 200-msec interval centered in the 1200-msec silent portion of the cycle
- Three articulation conditions in which onset of a 300-msec light presentation signaled subject to silently articulate "la"; conditions differed with respect to relation of timing of light and tone: in simultaneous condition, light and tone were synchronized; in same-period condition, light and tone shared same 1.5 sec temporal period, but were out-of-phase, with light leading tone by 600 msec, so that the light offset-tone onset interval was 300 msec; in different-period condition, light and tone had harmonically unrelated periods (2 subconditions: a light period of 1.3 sec, which was shorter than tone period, and a light period of 1.7 sec, which was longer than tone period); in a control condition, no articulation was required
- Measurements taken 5-10 sec after tone onset, then number of alarm (error) signals recorded during next 20 on/off cycles for tone, then another 5-10 sec of unmeasured performance; trial lasted 45 sec

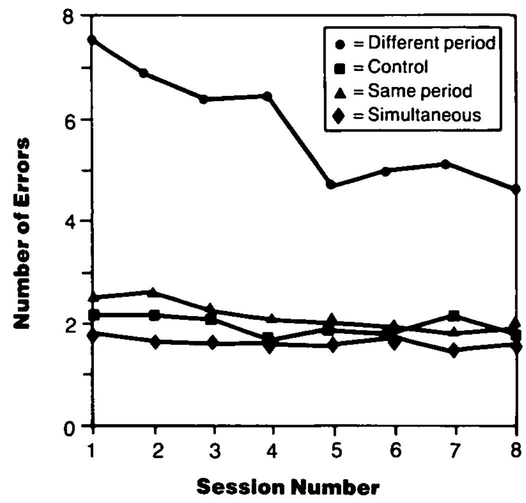

Figure 1. Number of errors for key press task as a function of practice and periodicity of articulation task with respect to manual task. (From Ref. 1)

Experimental Procedure

- Independent variables: articulation condition, session number (practice)
- Dependent variable: number of errors, measured in terms of number of alarm signals during 20 tone cycles per condition
- Subject's task: depress key in synchrony with tone presentation and silently articulate "la" concurrently with light (except for control condition)
- 8 right-handed college students; one subject quit because task was too difficult

Experimental Results

- Performance is much worse when the manual and articulation responses have different periodicity.
- Performance improves with practice during the first five sessions ($p < 0.05$), but this is mostly (if not completely) due to improvement in the different period conditions.
- Performance in all four conditions is stable for the last three experimental sessions.

Variability

An analysis of variance was used; mean square errors were not reported.

Repeatability/Comparison with Other Studies

Similar results were obtained with voiced articulation and unsignaled simultaneous silent articulation of "la" as quickly as possible throughout testing (Ref. 1). In tasks where a manual and a vocal response are required, the two responses are temporally grouped (CRef. 9.120). Movements of the right and left hands interfere with each other less if they are performed simultaneously or with harmonically related rhythms (CRef. 9.305). It is difficult not to coordinate movements of the two hands, even when two manual tasks require different temporal patterns (CRef. 9.202).

Constraints

- With two-handed tasks, the same-periodic, phase-displaced condition, which avoids overlap, yields the best performance. It is not clear in this study whether the lack of advantage for the same-period, no-overlap condition is attributable to articulation performance not being measured or because even intervals aided the two-handed task and irregularity of intervals prevented the advantage.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Klapp, S. T. (1981). Temporal compatibility in dual motor tasks II: Simultaneous articulation and hand movements. *Memory and Cognition*, *9*, 398-401.

Cross References

9.120 Reaction time for coupled manual and vocal response: effect of stimulus probability;

9.202 One- versus two-handed reaching: effect of target distance and width;

9.305 Coordination of hand movements on timed tasks

9.401 Model of the Effects of Practice on Task Performance

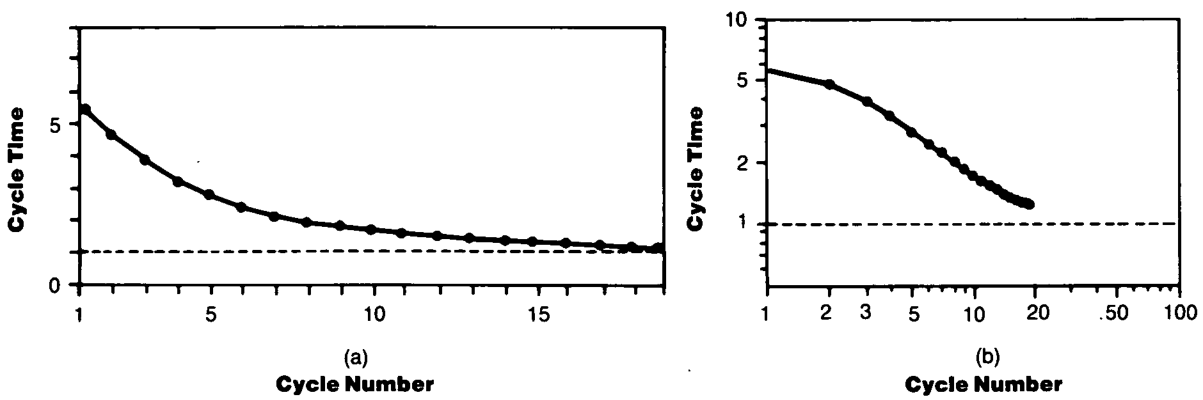

Figure 1. Learning curves for the model on (a) linear and (b) log-log coordinates. The curves approximate the characteristic shapes of learning curves for experimental practice data. (From Ref. 4)

Key Terms

Learning; practice; repetitive skill; training

General Description

Some people complete motor tasks (e.g., cigar making, card sorting, parts assembly) faster than others, not because they have had more practice, but because practice has suggested to them better methods of performing a task. The learning of repetitive skills is theoretically a result of choosing methods that minimize the total time necessary to do the task. As learning increases, the probability of selecting more efficient methods increases. The constituent decisions and movements of efficient workers can be taught to others to speed their learning.

Mathematically, at any stage of practice (cycle n), the average time (T_n) for a task equals the sum of the product of the time for each possible method (t_m) times the probability of each method (p_m), or

$$T_n = \sum_{m=1}^{M} t_m p_m \qquad (1)$$

with the assumption that the sum of the probabilities for all methods in the repertoire of the operator is 1.0. For each repetition of the task (i.e., for each cycle), the probability of selecting a particular method is changed in proportion to the difference between the time for that method and the average time, or

$$\delta p_m = -k(t_m - T_n) \qquad (2)$$

where k is a small positive constant. Thus the average change in the probability of any method (p_m) on cycle n is

$$(p_{m,n})(\delta p_m) = -k(p_{m,n})(t_m - T_n) \qquad (3)$$

and the probability of Method m for the next cycle $(n + 1)$ is

$$(p_{m,n+1}) = (p_{m,n}) + \delta(p_m) = (p_{m,n})[1 - k(t_m - T_n)]. \qquad (4)$$

(No normalizing expression is needed because the sum of the $(p_{m,n+1})$ is always 1.0.) Through the application of these formulas, unsuccessful methods will drop out and with practice there will be a steady decrease in the average time to complete the task.

The theory leads to several conclusions. First, the more sub-tasks and the more variance in the methods available for each sub-task, the slower will be the learning. Making the sub-tasks independent rather than interactive will speed learning. Second, transfer of skills from one task to another is dependent on both the similarity of the methods available for the two tasks and the selectivity patterns established for the original task.

Applications

The model implies that improved performance on a task is a consequence of better method selection rather than of practice per se. Thus a more efficient performance can be broken into component parts (as in time and motion analysis) and taught to other operators. This should decrease the amount of practice needed to achieve equivalently efficient performance. The model may be generalized by increasing an operator's ability to select methods (e.g., by increasing awareness of the process).

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Empirical Validation

The model has been empirically validated by comparing its predictions with the experimental findings for practice data. Using Eqs. (1) through (4), the average time for the next cycle ($n + 1$) is calculated as

$$T_{n+1} = \sum_{m=1}^{M} (p_{m,n+1})t_m = T_n - k(\text{variance of } t_m). \quad (5)$$

The learning curves in Fig. 1 were produced by the model for a beginning repertoire of ten equally probable methods with time represented by integers 1 to 10 and $k = 0.1$. The power functions yielded by the model approximate those often found for experimental practice data.

Constraints

- In actual situations, the operator's repertoire of methods may change (e.g., for sub-tasks) so that there are several independent selection processes occurring at the same time. Factors such as instruction, reasoning, chance, and forgetting may also alter the operator's repertoire at any point in the task. Other factors, such as fatigue, may also influence selection.
- The formulas are based on the assumption of selection acting within the complete cycle. If selection acts on elements of the cycle, the distributions of times would be combined differently.
- Some tasks, such as typing and handwriting, seem to have limits related to individual maximum tapping rates (CRef. 9.302).

Repeatability/Comparison with Other Studies

A similar analysis was used to investigate text editing on computers (Ref. 3) and to evaluate alternate methods for cursor positioning in editing programs (Ref. 2).

Key References

*1. Blackburn, J. M. (1936). *Acquisition of skill: An analysis of learning curves.* Industrial Health Research Board (IHRB) Report, No. 73.

2. Card, S. K., English, W. K., & Burr, B. (1978). Evaluation of mouse, rate-controlled isometric joystick, step keys, and text keys for text selection on a CRT. *Ergonomics, 21*, 601-613.

3. Card, S. K., Moran, T. P., & Newell, A. (1980). Computer text-editing: An information processing analysis of a routine cognitive skill. *Cognitive Psychology, 12*, 32-74.

*4. Crossman, E. R. F. W. (1959). A theory of the acquisition of speed-skill. *Ergonomics, 2*, 153-166.

5. Dudley, N. A. (1955). *Output patterns in repetitive tasks.* Unpublished doctoral dissertation, Birmingham University, England.

Cross References

9.302 Tapping rate, typing speed, and handwriting speed;

9.539 Effect of practice on tracking

9.402 Motor Skill Development with Massed Versus Distributed Practice

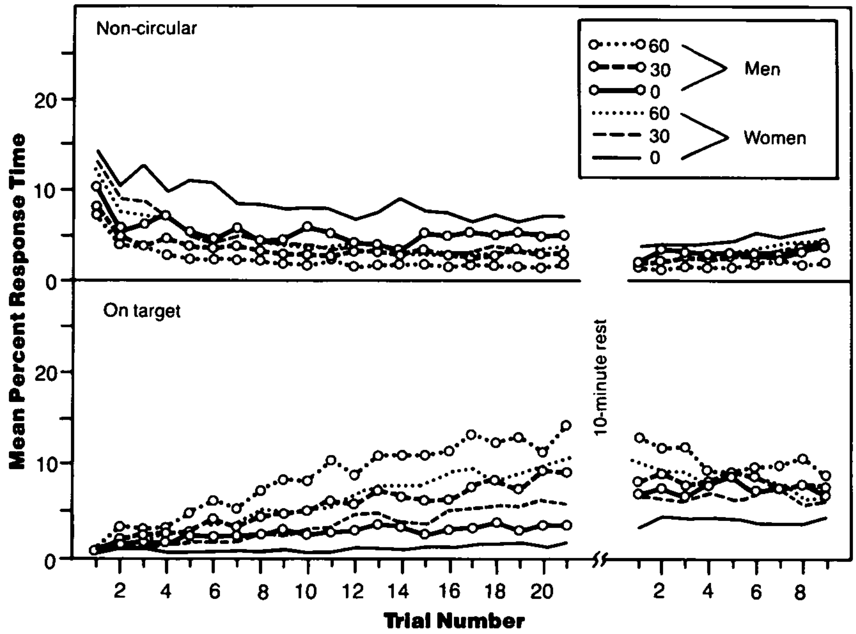

Figure 1. Mean percent response time for both men and women spent on non-circular movements and on target (circular movements) as a function of trial number and rest-interval duration. The values 0, 30, and 60 indicate the duration of the rest intervals between trials (in seconds); the 0 interval is massed practice (no rest intervals). (From Ref. 1)

Key Terms

Massed practice; motor skills; practice; pursuit eye movements; training

General Description

Motor skills, particularly fatiguing ones, are learned best with periods of rest distributed throughout sets of trials (rather than performing all trials together with no intervening rest, called massed practice). To help performance, rests during practice must be frequent and long enough for fatigue to dissipate. Much of the performance decrement with massed practice is short term; performance after a rest is often better than performance at the end of the massed practice session. There is also, however, a long-term component. For equal amounts of time spent in massed and distributed practice, less time is spent actually practicing in the massed condition than in the distributed condition, because accumulated fatigue prevents practice.

Applications

Improving learning by arranging training as distributed practice.

Methods

Test Conditions

- Pursuit rotor tracking task in which subject tracked a 1.91-cm (0.75-in.) target on a turntable rotating at 80 rpm; stylus hinged so that subject could not press down on target
- Oral warning signal and beginning and ending signals for trials
- Twenty-one 30-sec trials with either 0-, 30-, or 60-sec rests between trials, then 10-min rest followed by nine trials with no intertrial rest periods
- One intertrial rest duration per subject

Experimental Procedure

- Pursuit rotor tracking
- Between-subjects design
- Independent variables: sex, duration of intertrial rest periods, trial number
- Dependent variables: time on target, time spent on noncircular movements, frequency of noncircular movements, frequency distribution of noncircular-movement durations
- Subject's task: keep stylus in contact with moving target
- Subject encouraged to look at magazines during rest interval to prevent visual tracking of target
- 45 male and 45 female undergraduates with no practice, equally distributed over intertrial rest period conditions

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Experimental Results

- Men make fewer and shorter noncircular movements than women do on all trials (including the first trial which should show no effect of practice).
- For each intertrial rest duration condition, men spend more time on target than women do, but functions for men and women have the same slopes and changes in slopes (Fig. 1).
- Means, slopes, and changes in slopes for time on target increase (i.e., performance improves) as intertrial rest duration increases.
- Frequency of noncircular movements decreases as intertrial rest duration increases, and also decreases over trials at a negatively accelerated rate.
- Time spent in noncircular movement is inversely related to intertrial rest duration, decreases rapidly over trials, and has a lower asymptote for longer rest intervals.
- Time-on-target on the nine trials after the 10-min rest is inversely related to intertrial rest duration; time on target increases most at the 0-sec interval and decreases for the 60-sec interval.

Variability

Extended trends analyses of variance were used.

Repeatability/Comparison with Other Studies

Initial performance 2 yrs after concentrated practice on the pursuit rotor task was better than at the end of the first 5 min of practice (Ref. 2).

Constraints

- Length of rest was varied, but except for the difference between the no-rest and rest conditions, frequency of rests was not explored.

Key References

*1. Archer, E. J. (1958). Effect of distribution of practice on a component skill of rotary pursuit tracking. *Journal of Experimental Psychology, 56*, 427-436.

2. Koonce, J. M., Chambliss, D. J., & Irion, A. L. (1964). Long-term reminiscence in the pursuit rotor habit. *Journal of Experimental Psychology, 67*, 498-500.

Cross References

9.539 Effect of practice on tracking

9.403 Response Chunking in the Training of Complex Motor Skills

Key Terms

Complex skill; coordinated hand movement; practice; response differentiation; training

General Description

Performance of complex skills improves as a power function of practice. Finer analysis of a laboratory analogue of complex perceptual-motor skills, a 1,023-choice reaction time (RT) task, reveals that the power law of practice appears to reflect a learning-by-chunking process. Responses are organized in chunks which mirror the structure of the task. These chunks become more elaborate, spanning longer movement sequences, with increased practice.

Applications

Acquisition of perceptual-motor skills may be facilitated when the training sequence is tailored to build increasingly-efficient response chunks.

Methods

Test Conditions

• Stimulus patterns were simultaneous presentations of some combination of ten lights, scaled to fall within 16 deg of visual angle (Fig. 1); pattern displays randomly selected from 1,023 possible patterns of illumination
• Responses were keyboard presses (Fig. 1), with keys corresponding to each of the ten lights and each of the subject's ten fingers; set of key presses for a trial imitated the light illumination pattern
• Subject rested fingers lightly on response keys between trials

Experimental Procedure

• Within-subjects design
• Independent variables: pattern of illumination, trial number
• Dependent variables: RT, spatial pattern of responding within trials
• Subject's task: press keys to imitate the pattern in which the ten lights were illuminated
• Subject was instructed to respond as quickly as possible while maintaining a low error rate; error feedback after each trial
• 4 subjects, male graduate students, with no practice

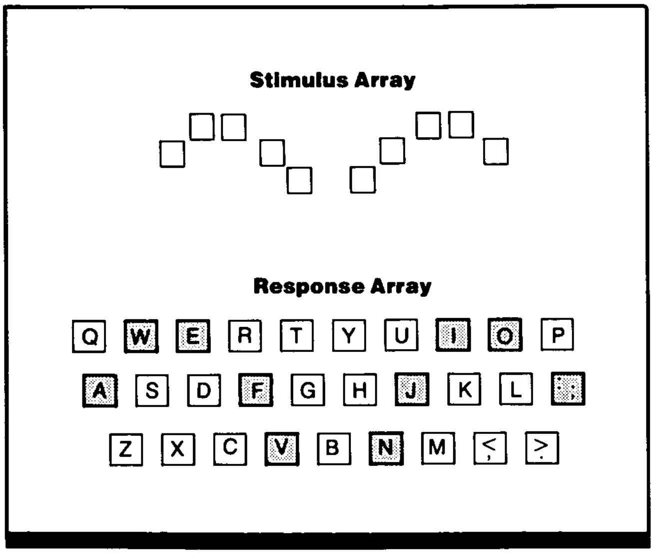

Figure 1. Stimulus array of ten lights (above) and response array (below) with ten highlighted keys, one for each light and each key to be depressed by a different finger. (From Ref. 3)

Experimental Results

• RT decreases as a power function of number of trials (CRef. 4.201).
• The more important within-trial response structures of typical trials are shown in Fig. 2. Subjects 1 and 2 responded in a pattern different from Subjects 3 and 4.
• Subjects tend to press groups of buttons nearly simultaneously, with temporal gaps occurring between these compound responses (response groups). The numbers above the bars in Fig. 2 indicate the temporal response group to which each key press belongs. Response groups fall in 4 classes: (1) response to a single light, (2) response to a group of adjacent lights, (3) responses to all of the lights for one hand, and (4) responses to all of the lights. In Trial 10, all responses by Subject 3 are responses to single lights (Class 1). By Trial 351, Subject 3 responds to all lights at once (Class 4).
• The number of fingers in a grouping increases with practice.
• Displays are generally processed from left to right.

Variability

Individual subjects used qualitatively different strategies, but all showed an increase in size of response groupings with practice.

Repeatability/Comparison with Other Studies

The decrease in RT as a function of number of practice trials is included in results reported in a much more extensive study of practice effects in the 1,023-choice task (Ref. 4).

Constraints

• Only a few trials were conducted.
• There was considerable within-trial variability across subjects; distributions for Subjects 1 and 2 were very different from distributions for Subjects 3 and 4.
• The presence or growth of response groups does not provide direct evidence of chunking.
• The range of trials over which chunk information has been studied is a very limited portion of the practice curve.
• Chunking may decrease accessibility of information so stored.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Anderson, J. P. (1983). *The architecture of cognition.* Cambridge, MA: Harvard University Press.

*2. Newell, A., & Rosenbloom, P. S. (1981). Mechanisms of skill acquisition and the law of practice. In J. R. Anderson (Ed.), *Cognitive skills and their acquisition* (pp. 1-55). Hillsdale, NJ: Erlbaum.

*3. Rosenbloom, P. S., & Newell, A. (1983). Learning by chunking: A production-system model of practice. In D. Klahr, P. Langley, & R. Neches (Eds.), *Self-modifying production system models of learning and development.* Cambridge, MA: Bradford Books/MIT Press.

4. Seibel, R. (1963). Discrimination reaction time for a 1,023-alternative task. *Journal of Experimental Psychology, 66,* 215-226.

Cross References

4.201 Power law of practice;

Handbook of perception and human performance, Ch. 28, Sect. 4.4

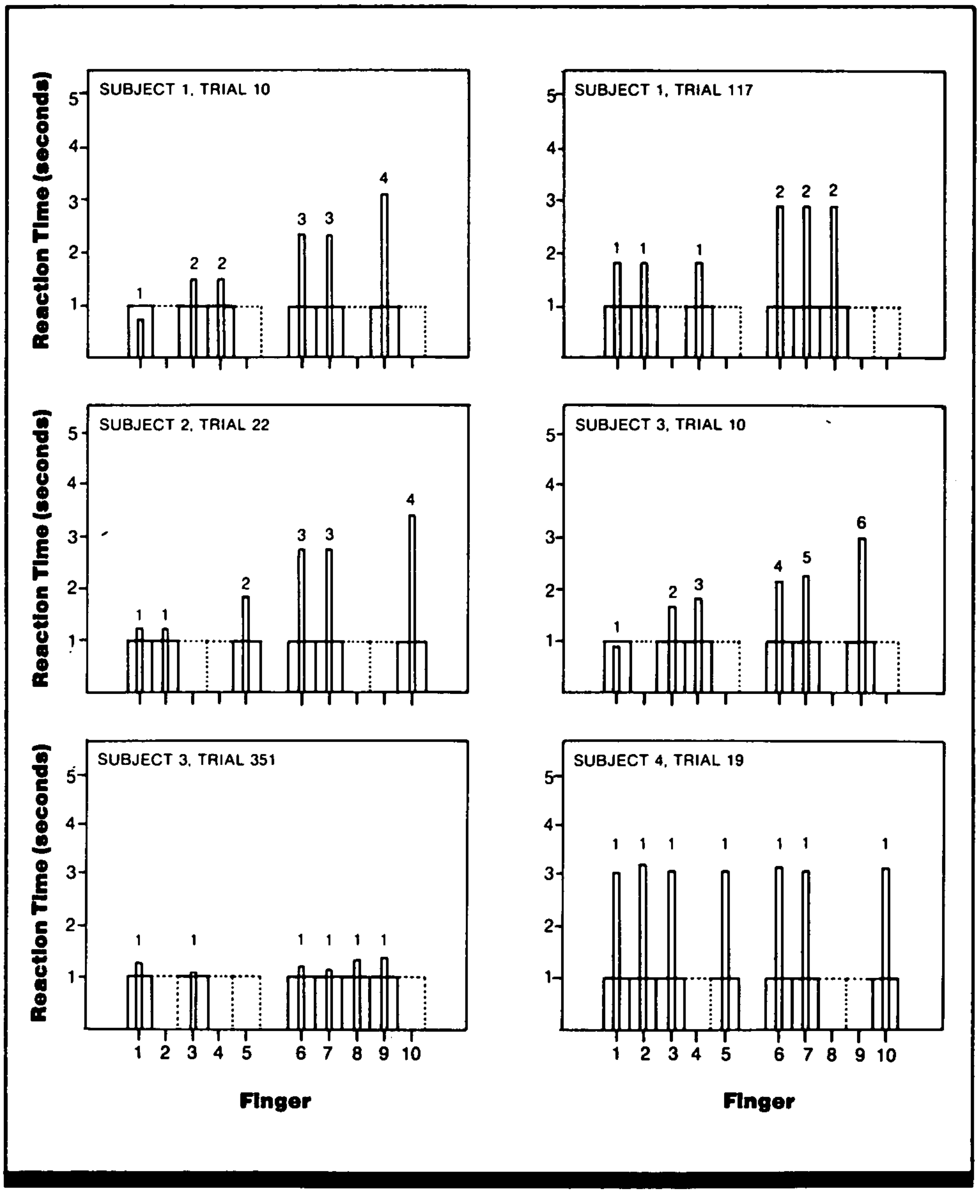

Figure 2. Illustrations of types of response patterns observed in the early trials of the 1,023-choice reaction time task. The ten short, wide bars represent the ten stimulus lights, separated for the two hands. Solid bars indicate illuminated lights; dotted bars, darkened lights. Narrow bars represent the reaction time to press the corresponding key. Numbers above each narrow bar designate the ordinate group, ranked from fastest to slowest. (From Ref. 3)

9.404 Effect of Knowledge of Results on Motor Learning

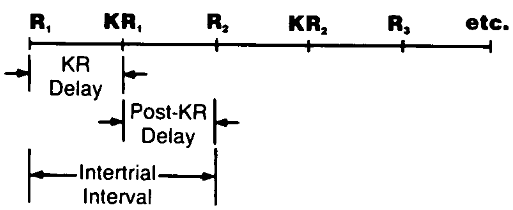

Figure 1. Temporal relations of responses (R), knowledge of results (KR) and intertrial interval. (From Ref. 5)

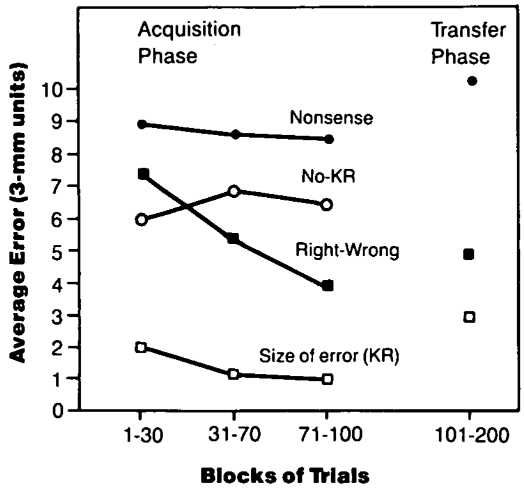

Figure 2. Average error of length of line drawn as a function of the type of knowledge of results during acquisition: no feedback, a nonsense word, right or wrong, or distance drawn when the line fell long or short of 7.6 cm (3 in.). Transfer trials, during which no knowledge of results was given, began 5 min after end of learning trials. (From Ref. 5)

Key Terms

Motivation; motor learning; training; visual feedback

General Description

Knowledge of results, delivered in experimental motor learning paradigms, is a form of feedback that is distinguishable from response-produced information (that which is received naturally when a response is made). Knowledge of results is information about response outcome, rather than about the nature of the movement, and is usually delivered verbally, at the end of a response. Thus, knowledge of results is feedback that is augmented rather than intrinsic, outcome-oriented, verbalized or verbalizable, and terminal rather than concurrent.

In general, studies show that knowledge of results enhances performance by increasing motivation or providing guidance. Most studies, however, have failed to distinguish between transient effects, which occur in the acquisition phase, and permanent (learning) effects, which continue after feedback is discontinued.

The table lists factors which influence the direction and strength of the knowledge of results effect on both acquisition and learning.

There are many methodological problems in studying the effects of knowledge of results:

1. The effects of knowledge of results and the effects of other types of feedback cannot always be differentiated.
2. Knowledge of the results-delay interval, the postknowledge of results delay interval, and the intertrial interval (Fig. 1) are interdependent; therefore manipulating one of them usually affects at least one of the others.
3. Experiments have often not included a transfer phase so the effect on learning (versus transient effects) is not clear.
4. Experiments that study the effects of either relative or absolute frequency of the delivery of knowledge of results do not always control for the other type of frequency.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Variables which affect the knowledge of results effect on acquisition and learning. (From Ref. 5)

Variable	Effect	Source
Absolute frequency of presenting knowledge of results	Increased absolute frequency enhances acquisition as well as learning	Ref. 8
Relative frequency of presenting knowledge of results	Increased relative frequency enhances acquisition; decreased relative frequency enhances learning	Ref. 7
Interval between response and presentation of knowledge of results (KR-delay interval)	As interval increases, there is either no effect, or acquisition and learning are both degraded	Ref. 4
Interval between presentation of knowledge of results and subsequent response (Post-KR-delay interval)	An increase in the interval slightly enhances acquisition; it enhances learning if the KR delay is constant	Ref. 1
Intertrial interval	As intertrial interval increases, acquisition effects are mixed; learning is enhanced if KR delay is constant	Refs. 1, 4
Interpolated activities in KR-delay interval	If activities are demanding, acquisition is degraded; generally, learning is also degraded unless the task is to estimate performance errors	Refs. 2, 6
Interpolated activities in post-KR delay interval	If activities are demanding, acquisition is degraded; learning is not affected	Ref. 5
Trials interpolated between a given trial and its presentation of KR (trials delay of KR)	Acquisition is degraded; learning is enhanced	Ref. 3

Constraints

• In addition to the methodological problems listed in the General Description, the effects of kinetic, kinesthetic, and visual feedback acting in conjunction with knowledge of results need to be considered.

• Knowledge of results interacts with other types of stressors (CRef. *Handbook*).

• Other definitions of knowledge of results also are in the literature.

Key References

1. Dees, V., & Grindley, G. C. (1951). The effect of knowledge of results on learning and performance IV: The direction of the error in very simple skills. *Quarterly Journal of Experimental Psychology, 3*, 36-42.

2. Hogan, J. C., & Yanowitz, B. A. (1978). The role of verbal estimates of movement error in ballistic skill acquisition. *Journal of Motor Behavior, 10*, 133-138.

3. Lavery, J. J. (1962). Retention of simple motor skills as a function of type of knowledge of results. *Canadian Journal of Psychology, 16*, 300-311.

4. McGuigan, F. J. (1959). The effect of precision, delay and schedule of knowledge of results on performance. *Journal of Experimental Psychology, 58*, 79-80.

*5. Salmoni, A. W., Schmidt, R. A., & Walter, C. B. (1984). Knowledge of results and motor learning: A review and critical reappraisal. *Psychological Bulletin, 95*, 355-386.

6. Shea, J. B., & Upton, G. (1976). The effects on skill acquisition of an interpolated motor-short-term memory task during the KR-delay interval. *Journal of Motor Behavior, 8*, 277-281.

7. Taylor, A., & Noble, C. E. (1962). Acquisition and extinction phenomena in human trial-and-error learning under different schedules or reinforcing feedback. *Perceptual and Motor Skills, 15*, 31-44.

8. Trowbridge, M. H., & Cason, H. (1932). An experimental study of Thorndike's theory of learning. *Journal of General Psychology, 7*, 245-258.

Cross References

7.801 Effect of incentives on performance;

Handbook of perception and human performance, Ch. 44, Sect. 3.3

9.501 Tactile and Visual Tracking: Effects of Error Feedback

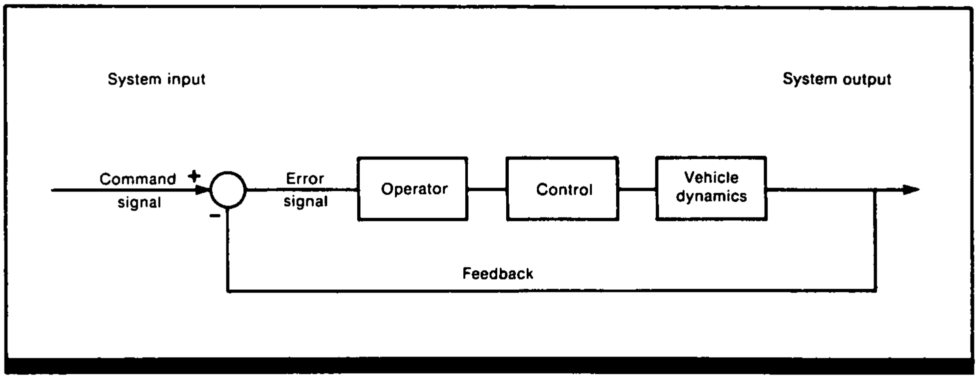

Figure 1. System diagram for tracking task. (From *Handbook of perception and human performance*)

Key Terms

Compensatory tracking; error feedback; knowledge of results; tactile displays; touch; tracking; visual tracking

General Description

In a stationary **compensatory tracking** task, the operator (subject) manipulates a control with the goal of minimizing an error signal (the difference between the input signal and the output of the simulated "vehicle" being controlled). Visual or tactile error signals generate similar performance when the feedback signal consists of the error signal plus its rate of change (quickened). Visual performance is better than tactile when the displayed feedback signal is the error signal alone (unquickened).

Methods

Test Conditions

- Control signal for the vehicle was the sum of multiple sine waves of different frequencies
- Vertical excursions of a horizontal line segment from a center position on a CRT provided visual error information
- For Ref. 1, activation of one or more of seven air jets provided tactile error information; display placement was either back of hand, palmar surfaces of three fingers, or forearm; the center jet of the display represented no error and the first and seventh jets represented maximal error with an inward-rippling pattern of activation that indicated the direction of the necessary correction; subject manipulated a joystick with the right hand to track
- For Ref. 2, tactile error information was provided by a servo-controlled solid rectangular section that slid in and out of the cylindrical handle of a joystick control; the thumb and opposing fingers contacted the moveable section and excursion of the section from the flush position indicated the direction and magnitude of error; subject moved the control stick in the direction of the protrusion to minimize the error.
- Monetary bonus given for best performance in each condition in Ref. 2

Experimental Procedure

- Independent variables: type of error signal feedback, modality of feedback
- Dependent variable: mean-squared tracking error normalized by the mean-squared input signal (Fig. 3), amplitude ratio (dB) and phase shift (degrees) describing functions
- Subject's task: manipulate a joystick so as to minimize an error signal
- For Ref. 1, 3 subjects (2 with some tracking practice and one with no practice) for the visual-feedback task, and 2 of the subjects also performed the tactile-feedback task; for Ref. 2, 36 right-handed undergraduates chosen for best performance on a pretest

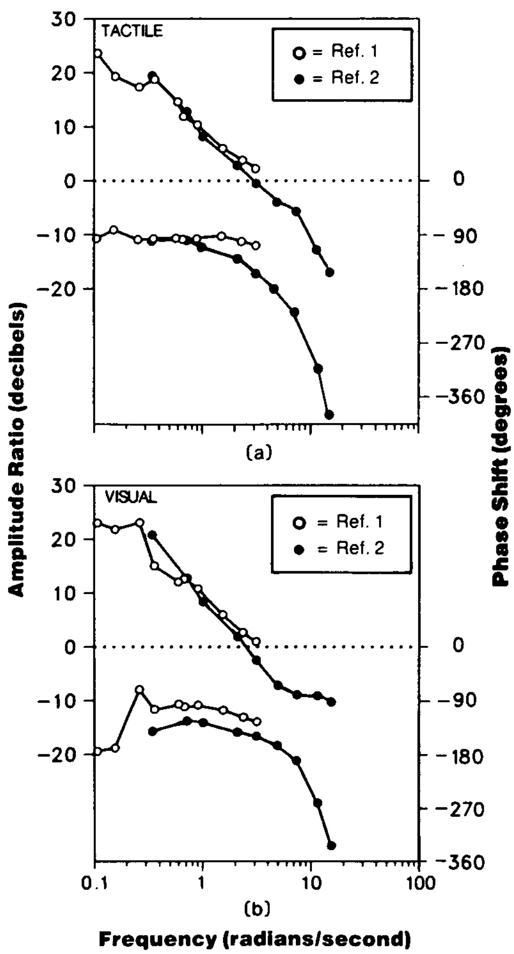

Figure 2. Describing functions for stationary tracking task performance for (a) tactile and (b) visual displays of error information. The upper portion of each panel is for amplitude and the lower portion is for phase. (From *Handbook of perception and human performance*)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Performance on a compensatory stationary tracking task is about the same for visual and tactile displays if the displayed feedback signal is the error plus its rate of change. Visual performance is superior to tactile if the feedback signal is error alone.
- Errors decrease monotonically as the feedback display is more rapidly updated.
- Wider spaces between the air jets also decrease error.

Variability

Figure 3 presents mean-squared error normalized by mean-squared input.

Constraints

- For Ref. 1, the visual-feedback task was performed first and the tactile-feedback task was performed after several intervening tactile-feedback tasks were completed.

Key References

*1. Hill, J. W. (1970). A describing function analysis of tracking performance using two tactile displays. *IEEE Transactions on Man-Machine Systems, MMS-11*, 92-101.

*2. Jagacinski, R. J., Flach, J. M., & Gilson, R. D. (1983). A comparison of visual and kinesthetic-tactual displays for compensatory tracking. *IEEE Transactions on Systems, Man, and Cybernetics, SMC-13*, 1103-1112.

Cross References

6.501 Modes of display for two-dimensional multielement tactile patterns;

6.502 Factors affecting identification of tactile patterns;

6.503 Identification of vibrotactile patterns: effect of display mode and body location;

6.505 Identification of vibrotactile patterns: temporal resolution;

9.538 Non-visual displays;

Handbook of perception and human performance, Ch. 31, Sects. 3.2, 3.3

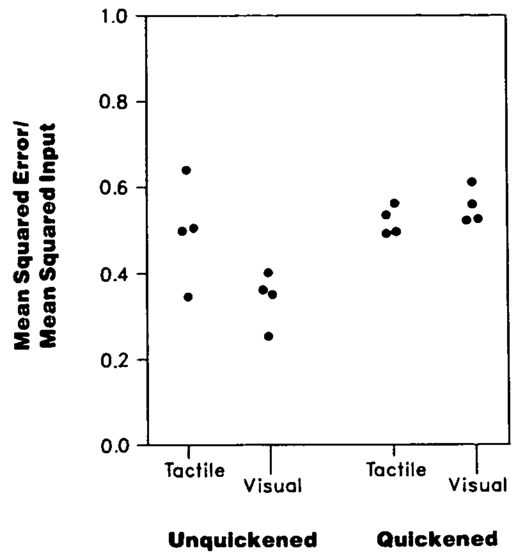

Figure 3. Comparison of tracking performance for visual and tactual displays. In the unquickened condition, the subject received only a value indicating the amount of error; in the quickened condition, the subject received a value that was the sum of the error signal and its rate of change. Each data point is for a different subject. (From R. J. Jagacinski, J. M. Flach, & R. D. Gilson, A comparison of visual and kinesthetic-tactual displays for compensatory tracking, *IEEE Transactions on Systems, Man and Cybernetics, SMC-13*. Copyright © 1983 IEEE. Reprinted with permission.)

9.502 Response of a Gain Element with Pure Time Delay

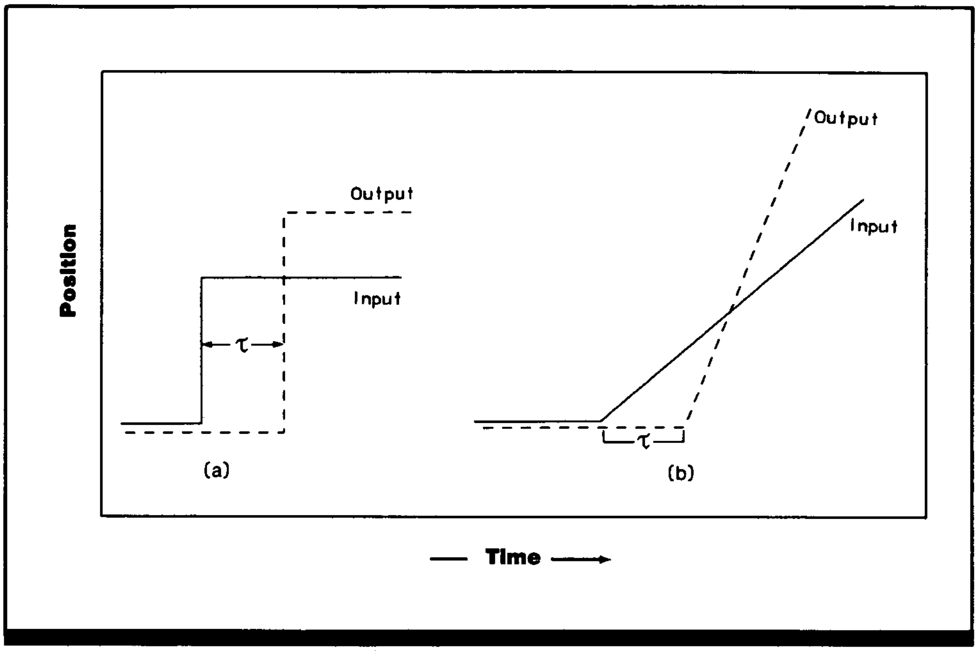

Figure 1. Response (output) of a system with a gain element K and a pure time delay τ. Position is shown as a function of time for (a) a step input and (b) a ramp input. (From *Handbook of perception and human performance*)

Key Terms

Bode plot; input-output; Laplace domain; phase lag; transfer function

General Description

The input and output of a manually controlled system can be represented by plotting signal position as a function of time. When a step input such as the one shown by the solid line in Fig. 1a (e.g., an aircraft suddenly blown off course by wind shear) is applied to a system that has an input-output relation represented by a **gain** factor K and a pure time delay τ, the output is illustrated by the dashed line that shows the same function multiplied by its gain and delayed by some time τ. When a ramp input such as the one shown by the solid line in Fig. 1b (e.g., input to a gunnery system tracking a constant velocity target) is applied to the system, the output is illustrated by the dashed line in Fig. 1b (which again is the input multiplied by its gain and delayed by time τ).

When a continuous sinusoidal input is applied (as shown by the solid line in Fig. 2), the output (the dashed line) is again the input multiplied by the gain and delayed by time τ. Therefore $B = KA$ and $K = B/A$ for each type of input (where the amplitude of the output is B; the amplitude of the input is A; and the constant gain factor is K).

The relationship between the output function of time and the input function of time is usually expressed in a differential equation. For the simple system shown here with a gain and a pure time delay, the equation is:

$$o(t) = Ki(t - \tau)$$

where $o(t)$, the output value at any time t, equals the gain factor K multiplied by $i(t - \tau)$, the input value τ seconds before.

The transfer function is an alternate form of the input-output relationship in the **Laplace** or **frequency domain**. The transfer function specifies the magnitude, or ratio of input to output ($B/A = K$ in Fig. 2), and the phase lag between input and output (related to τ in Fig. 2) expressed in degrees of a cycle. These two elements, magnitude and phase lag, may be represented together in a **Bode plot**, (CRef. 9.504) in which magnitude and phase lag are represented separately as functions of frequency.

Applications

Design of manually controlled systems; design of any moving system in which output is a linear function of some input signal.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. D'Azzo, J. J., & Houpis, C. H. (1966). *Feedback control system analysis and synthesis*. New York: McGraw-Hill.

2. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

Cross References

9.504 Bode plot representation of a gain element with pure time delay;

Handbook of perception and human performance; Ch. 39, Sect. 1.2

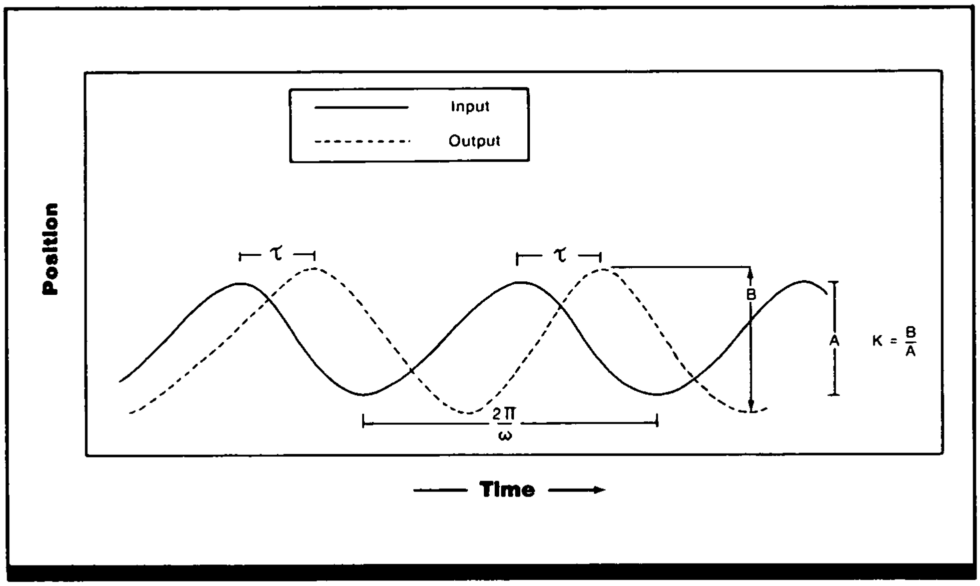

Figure 2. Response (output) of a system with a gain element K and a pure time delay τ. Position is shown as a function of time for sinusoidal input with period 2π/ω. A indicates the input amplitude; B indicates the output amplitude; K is the constant gain. (From *Handbook of perception and human performance*)

9.503 Response of a Pure Integrator Element

Key Terms

First-order system; process control; step input; system response; transfer function; velocity control

General Description

The input and output of a manually controlled system can be represented by plotting signal position as a function of time. When a step input (solid line, Fig. 1) is applied to a system with an input-output relation represented by a pure-integrator element, the output is a continuously increasing "ramp" response (e.g., moving a control stick a given distance to one side and holding it there makes the controlled vehicle change direction at a given rate). An example is the relationship between the angle of displacement of a car steering wheel and the car heading; if the steering wheel is held at a given angle for a period of time, the car will turn (change heading) at a constant rate. The differential equation for such a system is

$$O(t) = K \int i(t)dt$$

where O is the output at time t, K is a constant **gain** factor, and i is the input at time t.

Thus, the output depends on the length of time of the input step as well as its size (e.g., discrete or step input controls the rate of change of the output). This system is in the class of **first-order systems**, because it has a single time integration.

The response of a pure integrator system to a series of step inputs is illustrated in Fig. 2a and to sinusoidal inputs in Fig. 2b. The effect of input frequency on response amplitude is demonstrated by showing amplitude for inputs of different durations. Because there is a lag between the input and the time the output reaches its maximum value, the longer the peak input is sustained, the greater will be the maximum output (i.e., the higher the magnitude ratio). Thus, the magnitude of a first-order system is dependent on the frequency of the input. At low frequencies (longer peak inputs), the magnitude is high. At higher input frequencies (shorter peak inputs), the ramp output does not have as much time to increase before the input is reversed and thus the magnitude is lower. This is illustrated more readily with step inputs, but the implications are similar for sinusoidal (or for random) inputs. The transfer function (CRef. 9.502) contains both magnitude and phase lag information.

These transfer function characteristics may be summarized in a **Bode plot** (CRef. 9.504), which plots magnitude and phase lag as functions of frequency. Magnitude falls off with log frequency at a constant slope (−20 dB per decade). The phase of the input lags constantly behind the output by 90 deg (i.e., 1/4 cycle); this can be seen in Fig. 2a, where the peak output response occurs 1/4 cycle after the mean time, *PI*, of the peak input. Thus both magnitude and phase lag of the output are influenced by input frequency in a first-order or pure integrator system.

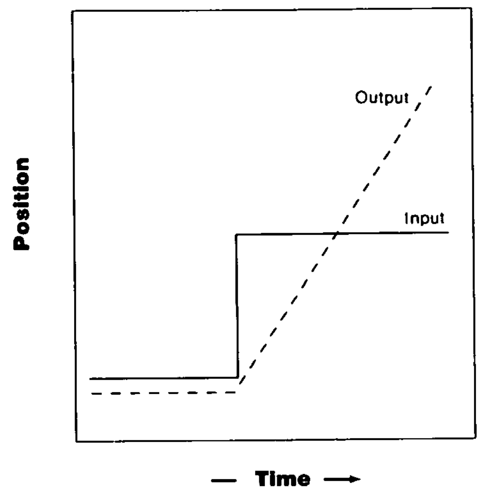

Figure 1. Response (output) of a first-order velocity control system (pure integrator element) to a step input; position is a function of time. (From *Handbook of perception and human performance*)

Applications

Design of manually controlled systems, including vehicles and process control systems.

Key References

1. D'Azzo, J. J., & Houpis, C. H. (1966). *Feedback control system analysis and synthesis*. New York: McGraw-Hill.

2. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

Cross References

9.502 Response of a gain element with pure time delay;

9.504 Bode plot representation of a gain element with pure time delay;

9.519 Control order;

Handbook of perception and human performance, Ch. 39, Sect. 1.2

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

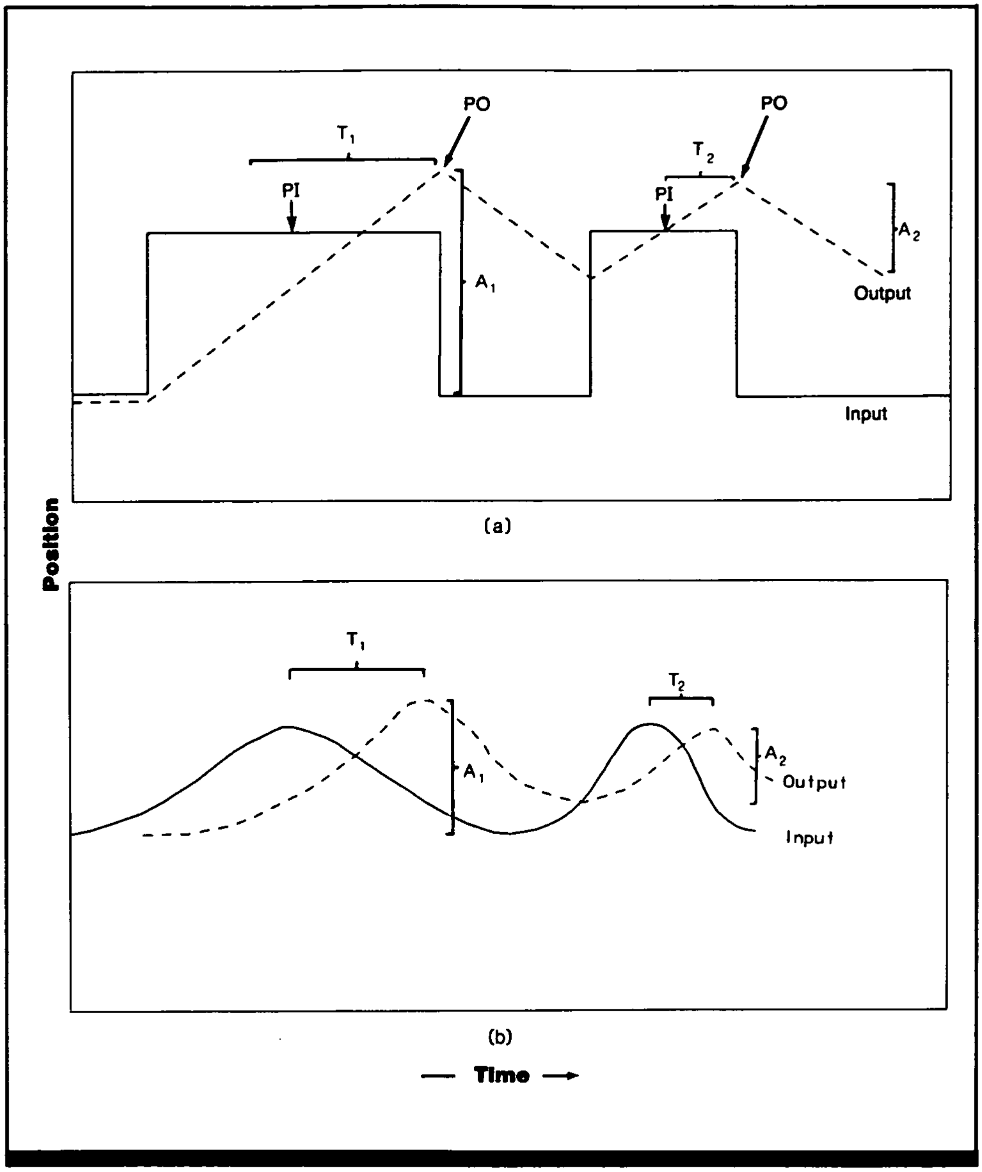

Figure 2. Response (output) of a first-order velocity control system (pure integrator element) to (a) a step function and (b) a sinusoidal input with multiple inputs of different durations; position is a function of time. *PI* indicates the average time of peak input; *PO* indicates the peak output; A_1 and A_2 indicate the amplitude of the response; and T_1 and T_2 indicate the lag of the peak output following *PI*. (From *Handbook of perception and human performance*)

9.504 Bode Plot Representation of a Gain Element with Pure Time Delay

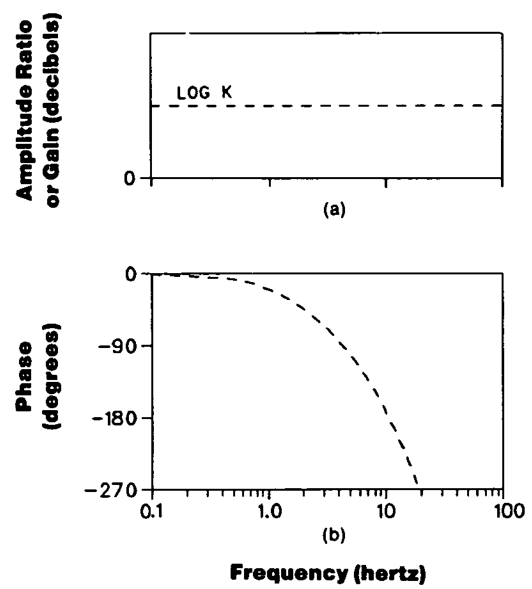

Figure 1. Bode plot representation for a system with a gain *K* and a pure time delay τ between the input and output. (a) The magnitude or amplitude ratio in decibels (20 x $\log_{10}$) as a function of the logarithm of frequency. (b) The phase lag in degrees as a function of the logarithm of frequency. (From *Handbook of perception and human performance*)

Key Terms

Bode plot; gain; Laplace domain; phase lag; tracking; transfer function

General Description

A sine wave input to a system characterized by a linear differential equation will cause a steady-state output which is another sine wave at the same frequency. However, the amplitude and phase of the output wave will usually differ from those of the input wave. Such a system may be described by the amplitude ratio and phase lag between the output and input. This information is called the transfer function, whose magnitude is the ratio of output amplitude to input amplitude and whose phase lag is the phase angle between input and output. Generally, these two elements will vary with the frequency, ω. Thus, the transfer function can be presented as a function of ω (in the frequency domain). The transfer function can also be presented as a function of s (in the Laplace domain) because these domains are related by the formula $s = i\omega$, where s = the Laplace variable, $i = \sqrt{-1}$, and ω = the frequency variable.

The transfer function may be represented graphically in a Bode plot, as illustrated in Fig. 1. Log frequency is plotted on the x-axis and (a) magnitude (expressed in decibels) and (b) phase lag (in degrees) are plotted on the y-axis for a system with the transfer function $O = Ki\,(t-\tau)$, where O = output, i = input, t = time, τ = time delay between input and output, and K is the gain factor.

For this particular function, the magnitude is constant over all frequencies, while the phase lag decreases as frequency becomes higher (as would happen in a zero-order system with a constant time delay). For higher-order systems, magnitude decreases with increasing frequency and the point at which the magnitude falls below 1 (0 dB) is called the crossover frequency. When the magnitude is >1 and the phase lag is >180 deg, a correction intended to reduce an error will be added to rather than subtracted from the error, thus resulting in an unstable system.

Applications

Design of dynamic tracking systems for vehicle or process control.

Key References

1. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

*2. Wickens, C. D. (1984). *Engineering psychology and human performance*. Columbus, OH: Merrill Publishing Company.

Cross References

9.502 Response of a gain element with pure time delay;

9.509 The kappa-tau space

Handbook of perception and human performance, Ch. 39, Sect. 1.2

9.505 Response of a Pure Differentiator Element

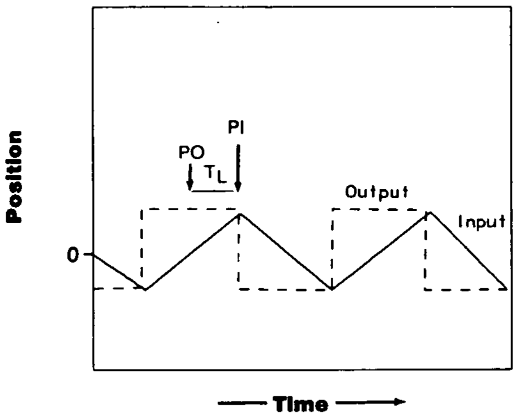

Figure 1. Response (output) of a minus first-order (derivative) system to periodic ramp inputs. Position is shown as a function of time. PI indicates peak input, PO indicates peak output and T_L indicates the lead time between the peak output and the peak input. (From *Handbook of perception and human performance*)

Key Terms

Bode plot; differentiator; first-order system; input-output; system order; transfer function

General Description

The input and output of a manually controlled system whose output is a differentiation of the applied input may be represented as a function of time (Fig. 1). A ramp input is shown by the solid line and the step-function response is shown by the dashed line. If the input were an ideal step function, which has an instantaneous change in position, and thus an infinite velocity, the output of the pure differentiator element would be an infinite spike.

As the operation of differentiation is the opposite of integration in calculus, the response of a pure differentiator element is opposite to that of a pure integrator element (CRef. 9.503). Note that the peak output (PO) of the differentiator anticipates or leads the peak input (PI) by 90 deg, or 1/4 cycle. The equation that describes the input-output relationship is the derivative with respect to t of the t function:

$$O(t) = di(t)/dt$$

where O = output, i = input, and t = time. The element can also be represented in a Bode plot (CRef. 9.504) which plots magnitude and phase lag as functions of frequency.

A pure differentiator element is seldom encountered in real systems, especially in manual control. However, such an element may be placed in series with an integral control element, or as a part of a **feedback loop**, thereby cancelling the integration and making the system easier to control. One example is the performance control system (PCS), which provides differentiation in feedback loops to pilots on the higher-order control tasks involved in controlling bank angle and vertical speed (Ref. 2).

Applications

Design of manually controlled systems, including vehicle and process control systems.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. D'Azzo, J. J., & Houpis, C. H. (1966). *Feedback control system analysis and synthesis*. New York: McGraw-Hill.

2. Roscoe, S. N., & Bergman, C. A. (1980). Flight performance control. In S. N. Roscoe (Ed.), *Aviation psychology*. Ames, IA: The Iowa State University Press.

3. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

Cross References

9.503 Response of a pure integrator element;

9.504 Bode plot representation of a gain element with pure time delay;

Handbook of perception and human performance, Ch. 39, Sect. 1.2

9.506 System Feedback: Open- and Closed-Loop Transfer Functions

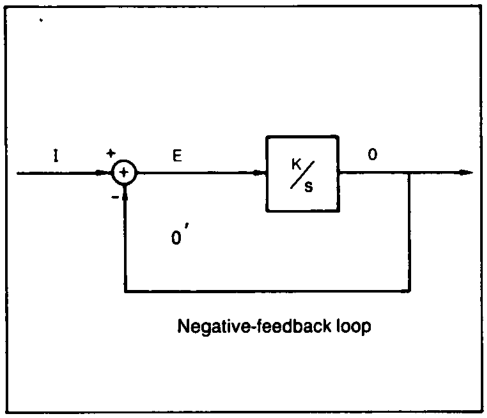

Figure 1. A closed-loop system (i.e., an open-loop system *K*/s with a negative-feedback loop). *I* = input, *E* = error (i.e., output minus input), *K* = gain, 1/*s* = Laplace representation of a pure integrator, *0'* = feedback, and *0* = output. (From *Handbook of perception and human performance*)

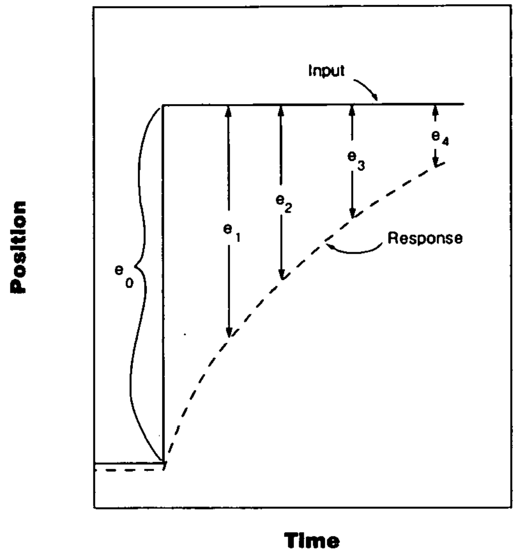

Figure 2. An approximation of the closed-loop response (output) of the system shown in Fig. 1. The velocity at time *t* is proportional to the amount of error e_t. (From *Handbook of perception and human performance*)

Key Terms

Feedback; negative feedback; simulation; stability

General Description

Feedback is often used to stabilize an unstable system or to reduce the error in a tracking system. Negative feedback is generally used because when the input is replaced with the difference between the input and the output, the output tends to follow the input more closely. (The negative is obtained by subtracting the output from the input.)

The effect of negative feedback is illustrated with the *K/s* system (a pure integrator with gain; CRef. 9.503). Without any feedback, the response of this system to a step input is a continuously increasing output. However, when a feedback loop is added to this system (Fig. 1), an increase in the output causes a reduction in the error, *E*. Since this error is now the input to the integrating element, the rate of increase of the output is also reduced. Thus the output will asymptotically approach the input, and the closed-loop system is now stable.

Stability analysis of feedback systems is facilitated by examination of *open-loop transfer functions* and *closed-loop transfer functions*. The open-loop transfer function relates the feedback, *0'*, to the error, *E*. This is expressed in the Laplace domain as $0'/E$, and is extremely useful in assessing the stability of the closed-loop system. For this example the open-loop transfer function is $0'/E = K/s$. The closed-loop transfer function relates the output, *0*, to the input, *I*, expressed in the Laplace domain as $0/I$. The closed-loop transfer function characterizes the complete system with feedback.

When unity-gain negative feedback is used on a system with transfer function *G* (such as in Fig. 1), the closed-loop transfer function is:

$$CL = G/(1 + G)$$

For the above example, the closed-loop transfer function is:

$$CL = \frac{K/s}{1 + (K/s)} = \frac{K}{s + K}$$

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Design of aircraft and aircraft simulator displays; design of vehicle displays and controls; feedback circuit modification for easier vehicle handling; of particular importance for vehicles with complex dynamics, such as helicopters.

Constraints

- Increasing negative feedback gain generally reduces closed-loop system error. Thus a minimum feedback gain may be necessary for a given error criteron.
- Since feedback can be used to stabilize an unstable system, a minimum gain may be necessary to stabilize the system.
- Large feedback gains may reduce system stability, depending on the system dynamics. Thus, system stability may dictate a maximum feedback gain.

Key References

*1. Jagacinski, R. J. (1977). A qualitative look at feedback control theory as a style of describing behavior. *Human Factors, 19,* 331-347.

2. Toates, F. (1975). *Control theory in biology and experimental psychology.* London: Hutchinson Educational.

Cross References

9.502 Response of a gain element with pure time delay;

9.503 Response of a pure integrator element;

9.505 Response of a pure differentiator element;

Handbook of perception and human performance, Ch. 39, Sect. 1.3

9.507 Phase Margin: A Measure of Stability

Key Terms

Bode plot; controls; feedback; gain; magnitude; phase lag; phase margin; stability

General Description

A stable dynamic system has a finite (or bounded) output when a finite input is applied. Stability is important, particularly in manual control of any vehicle, because loss of stability generally results in loss of vehicle control. Although the introduction of negative feedback (CRef. 9.506) may stabilize an otherwise unstable system, it may also represent a source of instability. This instability is most likely to occur in a system with a combination of high gain and large phase lag.

Positive feedback almost always leads to instability, because the output is added to the input, thereby amplifying the error rather than correcting it. Such positive feedback loops require continuous compensatory control and are sometimes found in helicopter or other complex aircraft controls.

If a negative feedback system has an open-loop transfer function phase lag of 180 deg, the output and the error will be out of phase and the output is added to the input instead of subtracted from it. If the magnitude is <1, the counterproductive output is attenuated. However, if the magnitude is >1, the erroneous output is amplified and the output becomes unbounded. This is similar to positive feedback, and the system is unstable. In aviation, "pilot-induced oscillation" is an instability of this kind.

Predictions of system stability (or instability) may be made from a Bode plot (Fig. 1; CRef. 9.504), which shows the magnitude and phase lag as a function of log frequency. The frequency where the magnitude is 0 dB (corresponding to the x-intercept of the magnitude function in the Bode plot) is called the *crossover frequency*. A phase lag of 180 at this frequency is the transition between stability and instability. A phase lag >180 at the crossover frequency means the system is unstable.

The Bode plot of such an unstable system is shown in Fig. 1a. This system is unstable because above 10 Hz the magnitude is greater than 0 dB while the phase lag is greater than 180. The same system has become stable (Fig. 1b.) with a gain reduction, thereby providing a margin of stability. This margin, called the phase margin or phi, is the degree to which the phase lag is short of 180 at the crossover frequency. In the example of Fig. 1b the phase margin is approximately 40 and the crossover frequency is 6 Hz.

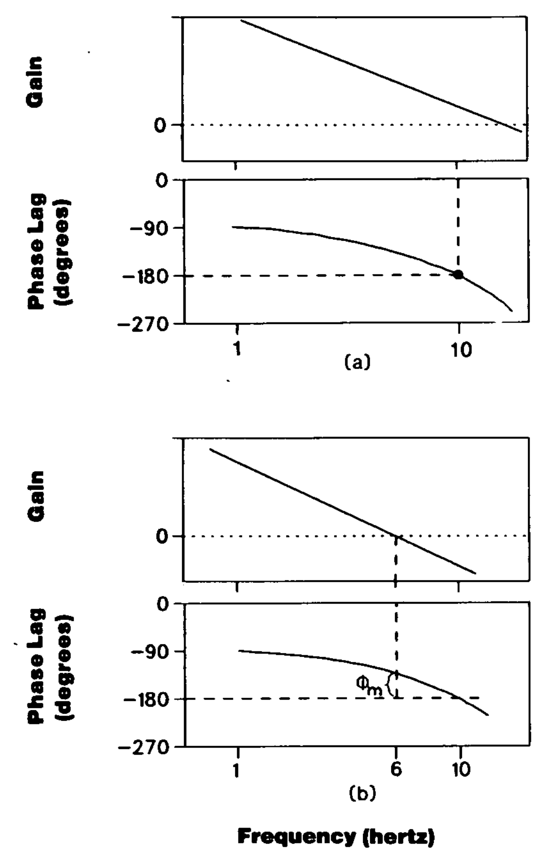

Figure 1. (a) Bode plot of an unstable system. At 10 Hz the gain is >1 and the phase lag is 180 deg. (b) A decrease in gain causes the system in (a) to achieve stability at 10 Hz. ϕ_m, the phase margin, is the margin of stability. (From *Handbook of perception and human performance*)

Constraints

- At low frequencies, the phase lag is likely to be smaller than it would be at higher frequencies. Consequently, a low crossover frequency generally results in a greater phase margin and the system is easier to control.
- Since feedback can be used to stabilize an unstable system, the Bode plot can show the minimum gain necessary to stabilize the system.
- Large feedback gains may reduce system stability, depending on the system dynamics. The Bode plot can be used to determine the phase margin for a given gain.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. D'Azzo, J. J., & Houpis, C. H. (1966). *Feedback control system analysis and synthesis*. New York: McGraw-Hill.

*2. Hess, R. A. (1981). An analytical approach for predicting pilot-induced oscillations. In T. Bejczy & J. Lyman (Eds.), *Proceedings of the seventeenth annual conference on manual control* (pp. 255-270). Washington, DC: National Aeronautics and Space Administration.

Cross References

9.503 Response of a pure integrator element;

9.504 Bode plot representation of a gain element with pure time delay;

9.506 System feedback: open- and closed-loop transfer functions;

9.513 Display gain;

Handbook of perception and human performance, Ch. 39, Sect. 1.3

9.508 Components of the Manual Control Loop Considering the Human Operator as an Element in the Control System

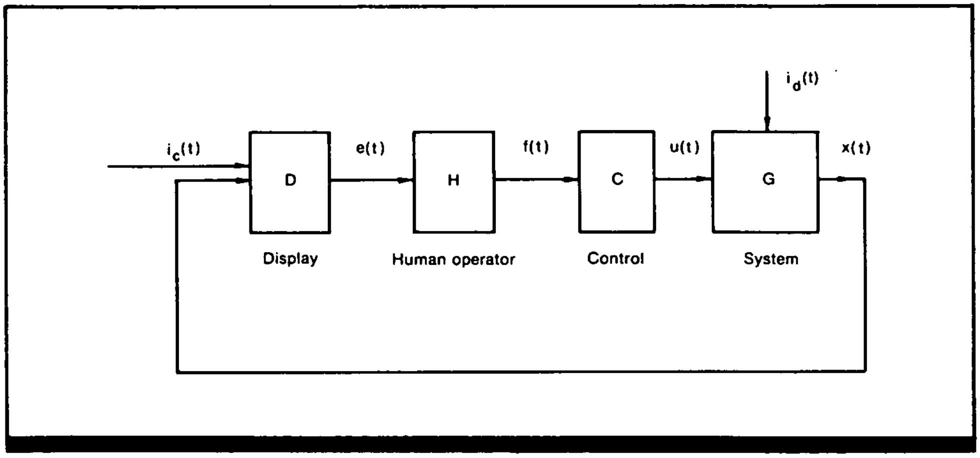

Figure 1. Representation of a tracking loop that includes a human operator. The inputs are target (command) input, $i_c(t)$, and disturbance input, $i_d(t)$. The outputs are error e(t), force f(t) applied to control, movement u(t) of the control, and system response x(t). (From *Handbook of perception and human performance*)

Key Terms

Compensatory tracking; controls; pursuit displays; stability; tracking

General Description

Manually controlling a physical system (e.g., regulating temperature in nuclear power plants or steering an aircraft, ship, or automobile) requires an operator to continually adjust a control to make it correspond on a moment-to-moment basis with some continuous reference signal. A major component of the task is to stabilize the system so that oscillations around the reference signal do not increase to the point where the system is out of control. This can be done by compensating for disturbances in system motion, (e.g., wind gusts on a straight glide path or pursuit of an evasive target).

This kind of task is called tracking, and human tracking behavior has been studied extensively, particularly with regard to aviation, where its critical nature was noted in pioneering research in engineering psychology in World War II.

A prototypical tracking task is illustrated in Fig. 1, where the human operator is part of the control loop in a closed-loop system. There is a time-varying command forcing function or target input, $i_c(t)$, (e.g., the road in a driving task) that is presented to the operator in a display. The operator then acts on the system by applying a force over time, $f(t)$, to some form of control (usually manual). The resulting control movement, $u(t)$, delivers a signal to the system, G, and the system response, $x(t)$, is generated and fed back to the display, where it is combined with the original input signal and displayed to the operator as error $e(t)$. There may also be a disturbance input to the system, $i_d(t)$, such as a gust of wind, and this also becomes part of the feedback. Target inputs must be followed and disturbance inputs must be corrected.

There are two modes of display that may be used to present error to the operator. If both target input, $i_c(t)$, and system response, $x(t)$, are presented, the display is in the pursuit mode; if only the difference $e(t)$ between them is displayed, the mode is called compensatory (CRef. 9.528). The corresponding system control is thus either pursuit tracking or compensatory tracking.

Applications

General control of dynamic systems, mainly vehicle control; automated process control.

Key References

*1. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

Cross References

9.528 Pursuit versus compensatory displays;

Handbook of perception and human performance, Ch. 39. Sect. 1.2

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

9.509 The Kappa-Tau Space

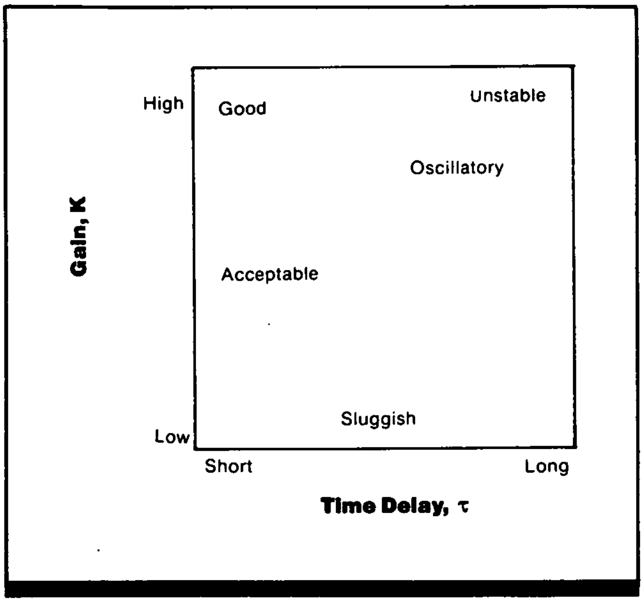

Figure 1. The K-τ space showing characteristics of tracking performance for a system including a human operator. The gain, K, and time delay, τ, can be independently varied. (From Ref. 1)

Key Terms

Gain; time delay; tracking

General Description

In a tracking task in which a human operator participates in the control loop (CRef. 9.508) problems of system stability can result from variations in pure time delay, τ, or in gain, K, which may be varied independently. Long time delays lead to oscillatory behavior and eventually to system instability, because of the phase lag between error and output. High gains may also lead to instability through overcorrection, especially if there are also time lags. In contrast, low gain systems seem sluggish because large inputs produce only small outputs.

The combination of the effects of variations in gain and delay can be shown in a figure called the K-τ space, which plots the gain of a system on the y-axis and the time-delay on the x-axis. Operator performance is indicated qualitatively within the space.

In the upper left region, with high gain and short time delay, tracking performance is good because errors are detected quickly and corrected easily. As time delay gets longer (approaching a 180-deg phase lag), the system begins to oscillate and eventually becomes unstable. If gain is reduced, stability may be restored to an acceptable level, but at the cost of sluggish performance, because a relatively high input is required for a small corrective action. Thus, the K-τ space summarizes the tracking performance of a closed-loop system as time delay and gain are independently varied.

Applications

Vehicle control and vehicle simulation; process control.

Constraints

- The K-τ space is a simplification. In particular, it does not take system control order (CRef. 9.520) into account.

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Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Jagacinski, R. J. (1977). A qualitative look at feedback control theory as a style of describing behavior. *Human Factors, 19,* 331-347.

2. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems.* Cambridge, MA: MIT Press.

3. Wickens, C. (1986). The effects of control dynamics on performance. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance.* New York: Wiley.

Cross References

9.507 Phase margin: a measure of stability;

9.508 Components of the manual control loop considering the human operator as an element in the control system;

9.514 Optimal gain levels in target acquisition;

9.520 Effects of system order and aiding on tracking performance

9.510 Error, System Control Criteria, and Human Limitations in Error Control

Key Terms

Error measurement; human error; system control; tracking; workload

General Description

In any man-machine system, three factors have a major influence on system performance: human error, system design (as described in terms of four criteria for ideal control behavior), and human limitations. In a manually controlled tracking system, human tracking error can be measured by the difference between input and output at each point in time. This error may be classified into three types. The first, a constant time delay, results in a phase lag by the operator in following the input (Fig. 1a). The phase lag increases with the bandwidth that is tracked; the low bandwidth on the left produces a small error and the higher bandwidth on the right produces a larger error. In the second error type, reduced gain, the input is reproduced perfectly in bandwidth, but with a lower amplitude (Fig. 1b). The third type, remnant or noise (Fig. 1c), is usually added to the first two, so that all three sources of error contribute to the total error in any particular human-machine combination. Error scores can be calculated a number of ways, with integrated error and root mean square (RMS) error commonly used:

$$\text{Integrated error} = \left(1/T\int_0^T \epsilon\, dt\right) \quad (1)$$

$$RMS = \left(\sqrt{1/T\int_0^T \epsilon^2\, dt}\right), \quad (2)$$

where T is the time period over which ϵ (error) is integrated.

There are four specific criteria to be considered in describing ideal control behavior. The first criteria, low error, can be quantified by computing an error score. The second criteria, stability of the system, is critical and is related to (but not necessarily caused by) high error. In Fig. 1b, for example, an attempt to decrease the error by increasing the gain might produce instability. Third, there is some optimal level of control activity for each system, such that necessary course corrections are made without excessive activity that might be fuel inefficient in vehicle control or lead to instability.

Finally, workload, which is the demand on the operator, should not exceed the operator's limited capacity. Workload is influenced by control dynamics and by perceptual and cognitive demands of the task. An operator may choose performance strategies that trade off the four ideal control criteria. For example, error could be increased by decreasing control activity or decreasing workload. Operators may also have strong preferences to use systems that more closely approach the ideal control system and will experience less stress and/or fatigue.

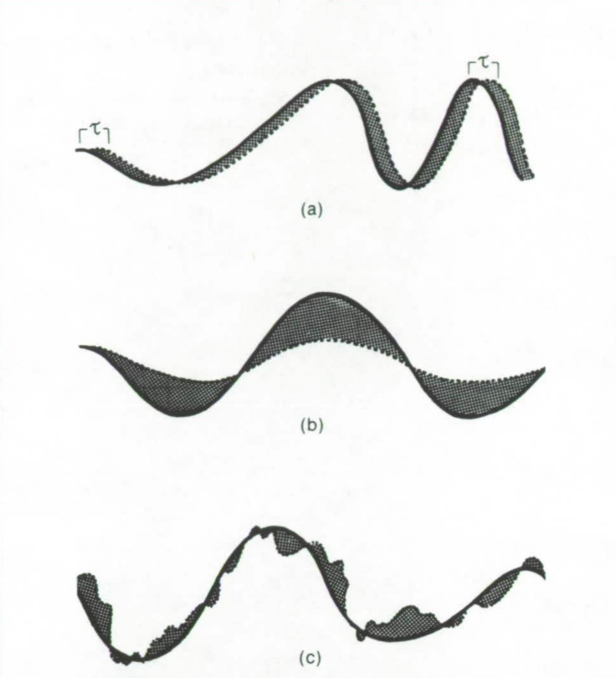

Figure 1. Inputs (solid lines) and outputs (dashed lines) of a tracking system with position as a function of time. The dashed areas indicate error resulting from (a) a time delay τ, (b) a reduced value of closed-loop gain, and (c) added remnant or noise. (From *Handbook of perception and human performance*)

Human operators have certain limitations that will affect both input to the operator and system output in a closed-loop system. Five of these limitations are extremely important. First, human operators have a built-in delay due to processing time. At signal bandwidths <1.0 Hz, lag does not induce much tracking error. However, at higher bandwidths, the delay may induce greater error and interact with system lags to produce instability.

Second, a human operator cannot respond when the rate of information transmission exceeds 4-8 bits/sec. Spatial uncertainty (number of bits per decision) is important, but number of decisions per sec is more important. The upper limit in a tracking situation is ~2½ decisions/sec in a task in which there is some spatial uncertainty. This limit is high enough to be rarely encountered outside the laboratory in normal tracking tasks such as vehicle control.

Third, it is difficult for human operators to predict vehicle location when there are other lag sources in a composite system, such as those introduced by higher-order dynamics. Prediction also imposes a higher mental workload and is subject to interference from other ongoing tasks.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Fourth, it is difficult for human operators to perceive higher-order derivatives. The human visual system has receptors that are directly responsive to velocity, although they impose a lag of 30-200 msec. Thus, it is possible for a human operator to predict vehicle motion directly in some systems. In contrast, acceleration is directly perceptible only through vestibular cues (i.e., in an actually moving vehicle). Finally, human operators have limited processing resources. Both attention span and time-sharing abilities for separate tasks are limited.

Applications

Measurement of error in a tracking system; design of tracking systems to reduce error; prediction of vehicle system performance from simulation performance.

Constraints

- Higher-order system dynamics impose reduced gains and increased phase lags that make a system harder to track.
- Requirements for prediction are more critical and impose a greater workload with higher-order systems.
- The workload imposed by a particular system is influenced by many factors, and should be measured independently for that system. It cannot be predicted solely on the basis of the tracking task.
- Bandwidth is a major contributor to workload.
- Bandwidth and system dynamics interact, so that increasing input bandwidth and introducing higher-order dynamics rapidly escalate control task difficulty.

Key References

1. McRuer, D. T., & Jex, H. R. (1967). A review of quasilinear pilot models. *IEEE Transactions on Human Factors in Electronics, HFE-8*, 231-249.

2. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems.* Cambridge, MA: MIT Press.

Cross References

7.101 Error classification and analysis;

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

9.513 Display gain;

9.519 Control order;

Handbook of perception and human performance, Ch. 39, Sect. 1.4

9.511 Modeling of the Human Operator: The Crossover Model

Key Terms

Bode plot; crossover frequency; describing function; phase lag; stability; tracking; transfer function; workload

General Description

The crossover model of human tracking behavior assumes that the operator of a dynamic system tries to achieve low error and *system stability* by behaving in a way that makes the operator and the system together respond as a **first-order system** in the input bandwidth region.

Because of the difficulty of modeling the human **transfer function** (the mathematical relationship between the input to and the output of a human operator), researchers (Refs. 1, 2) used the relationship between perceived error and system response to develop the crossover model (rather than the relationship between error and operator control). This is an **open-loop** (CRef. 9.506) transfer function, represented by $HG = X/E$, where H is the human operator and G is the system: X is the system output and E is the perceived error. Thus the crossover model (Fig. 1) allows the operator transfer function to adjust to the system transfer function to achieve stability and low error.

The relationship between the open-loop transfer function HG and the **closed-loop** function is given by $X/I = HG/(1 + HG)$. Therefore if the gain for the entire closed-loop (CRef. 9.506) function is to be equal to 1, which is necessary to achieve low error, the gain of the open-loop function must be infinite or very high (i.e., small errors should be corrected by large responses in the opposite direction). This will result in low error and tight control of the whole closed-loop system.

However, if there are open-loop phase lags approaching 180 deg or more, system stability will be a problem because error corrections will then be added to, rather than subtracted from, the input. As the frequency being corrected rises, the gain decreases to 0 dB (Fig. 2). The point at which gain becomes unity (0 dB) is called the crossover frequency (CRef. 9.507), and it is critical because the system becomes unstable if it is higher than the frequency at which the phase lag becomes greater than 180 deg.

The crossover model describes the combined HG system by the function $HG = K(e^{-\tau_e S}/S)$, which is a first-order system with a time delay. The function yields a high gain at low frequencies and a low gain at high frequencies, so the system has low error and is stable. However, there will always be some time delay, τ_e, so there will inevitably be a frequency at which phase lag is >180 deg. According to the crossover model, the operator will maintain a high open-loop gain so that crossover frequency is just below the frequency of 180 deg phase lag and a small phase margin is preserved. To do this, the operator adjusts to the system transfer function by lowering operator control order as system control order (CRef. 9.519) rises. (This adjustment is extremely difficult, if not impossible, in response to a third-order or higher system.) The equation is called a **describing function** rather than a transfer function because the human operator is not truly linear, and the model is thus a quasi-linear model. There is a portion of the human response that is linearly related to system input and is accounted for by the describing function, but there are also some nonlinear components collectively referred to as **remnant**. The remnant components contribute a relatively small proportion of the variance in the total response and are added to the output signal. Remnant sources are (1) variations in operator lags not related to input or system dynamics, (2) threshold effects in which small changes are disregarded, (3) intermittency of processing, (4) discrete impulse control, (5) random noise.

The describing function may be expanded to the more generalized form

$$H = K\frac{(T_L S + 1)\,e^{-(\tau_e S + \alpha/S)}}{(T_I S + 1)(T_N S + 1)},$$

where T_L and T_I are lead and lag time constants that may be set to provide equalization for various **system orders** (CRef. 9.520). With a first-order system, $T_L = T_I$ produces a pure gain response without any **equalization** by the human operator. The term α/S is "phase droop" (i.e., an increased lag observed at very low frequencies in higher-order systems). The term $T_N S + 1$ represents neuromuscular lag of the hand and arm. The fit of the model to human control of zero, first, and second order systems is illustrated in Figs. 2a, 2b, and 2c, respectively.

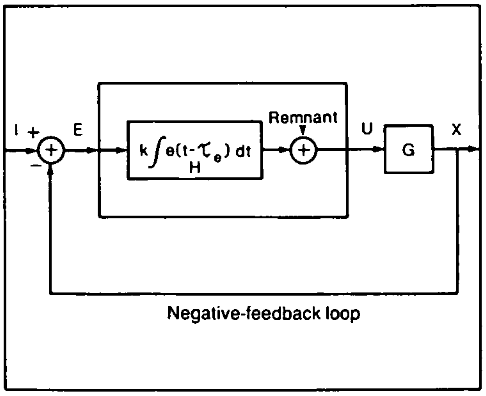

Figure 1. Closed-loop representation of the crossover model for a first-order function with gain and time delay. *I* = target input, *E* = error, *H* = human operator, remnant = noise in operator's response, *U* = control movement, *G* = the system, *X* = system output. (From *Handbook of perception and human performance*)

Applications

Stability of aircraft and other control systems can be predicted in the design stage from this model and knowledge of the transfer function of the system. Workload and associated problems such as the effects of fatigue and stress can also be predicted.

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Empirical Validation

Validation of the model involves placing human operators in a simulated system and varying parameters such as the transfer function of the system (as in Fig. 2). Closed-loop stability of aircraft can be predicted from coupling the model with the aircraft transfer function; pilot workload can be predicted from the lead time constant T_L. The model also predicts changes in the Bode plot (CRef. 9.504) as a result of operator factors such as stress, fatigue, dual task loading, alcohol, practice, etc. A moderate number of studies have been done which seem to bear out the model well.

Constraints

- The crossover model only applies to a stationary situation, where the task variables are constant and the pilot response characteristics are also stationary and repeatable.
- The effects of mode switching, short-term adaptation, learning of the pilot, or time-varying behavior in the task variables cannot be treated with this model.
- This quasi-linear model exhibits the main features of human operators, but does not model significant nonlinearities, which may be quite large for higher-order systems.
- This is a frequency domain model which does not easily account for time-domain behavior such as step responses or transient ramp inputs.
- The model requires a −20 dB/decade slope for the combined controlled-element transfer function and operator (describing-function) response.
- As an empirically developed model, it is based on observed human responses rather than on an analysis of the processing mechanisms used by the operator.
- Little account is taken of different individual operator styles or strategies.

Key References

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2. McRuer, D. T., & Jex, H. R. (1967). A review of quasi-linear pilot models. *IEEE Transactions on Human Factors in Electronics*, *HFE-8*, 231-249.

3. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

Cross References

9.504 Bode plot representation of a gain element with pure time delay;

9.506 System feedback: open- and closed-loop transfer functions;

9.507 Phase margin: a measure of stability;

9.519 Control order;

9.520 Effects of system order and aiding on tracking performance;

Handbook of perception and human performance, Ch. 39, Sect. 1.6

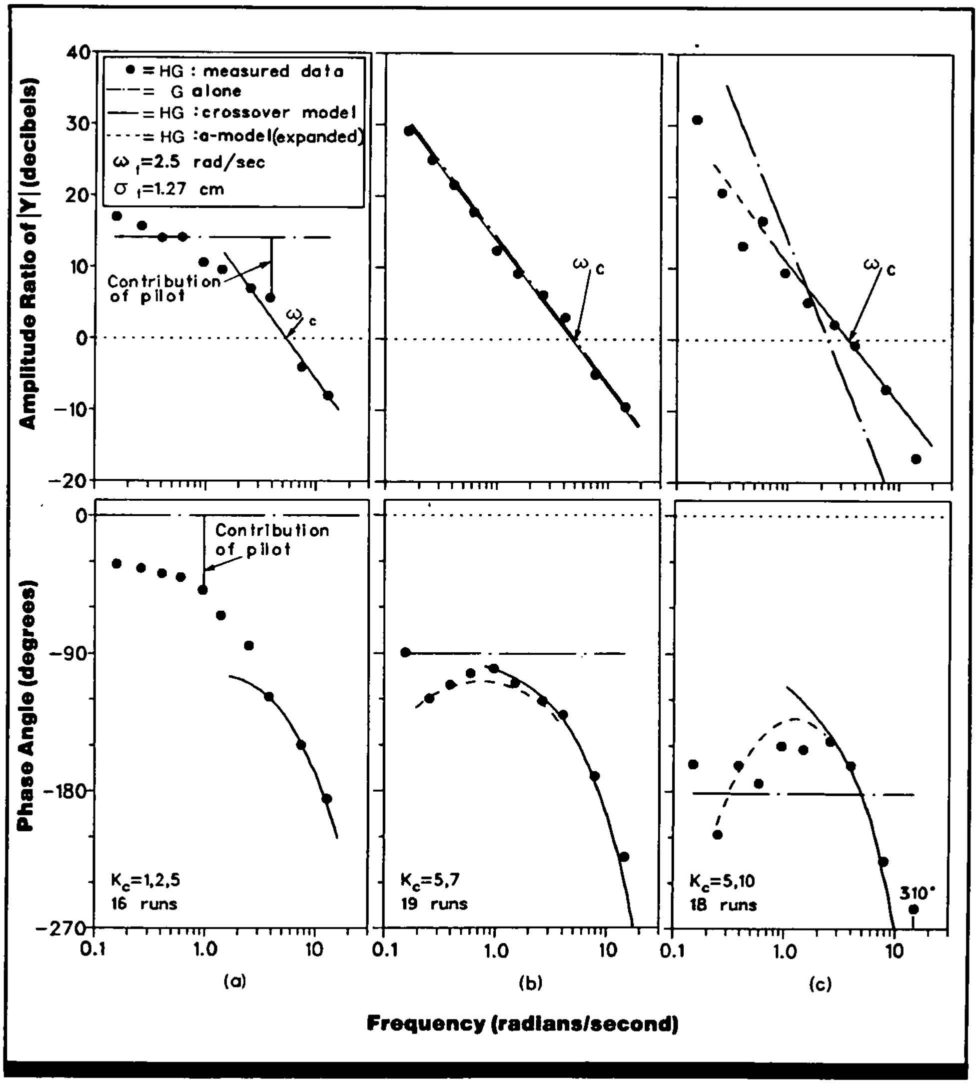

Figure 2. Bode plots of the describing function of the human operator tracking systems of (a) zero-order, (b) first-order, and (c) second-order dynamics. The contribution of the human operator is shown by the difference between the system G alone (dash-dot line) and the human *H* and system G together (data points). ω_c = the crossover frequency, and K_c = gain of controlled element. Data are for one well-trained pilot. The pilot's equalization is a lag for the zero-order system, none for the first-order system, and a lead for the second-order system. Dashed curves in (b) and (c) are predictions of an expanded version of the crossover model that accounts for increased phase lag at low frequencies. (From D. T. McRuer & H. R. Jex, A review of quasi-linear pilot models, *IEEE Transactions on Human Factors in Electronics*, *8*. Copyright © 1967 by IEEE. Reprinted with permission.)

9.512 Modeling of the Human Operator: The Optimal Control Model

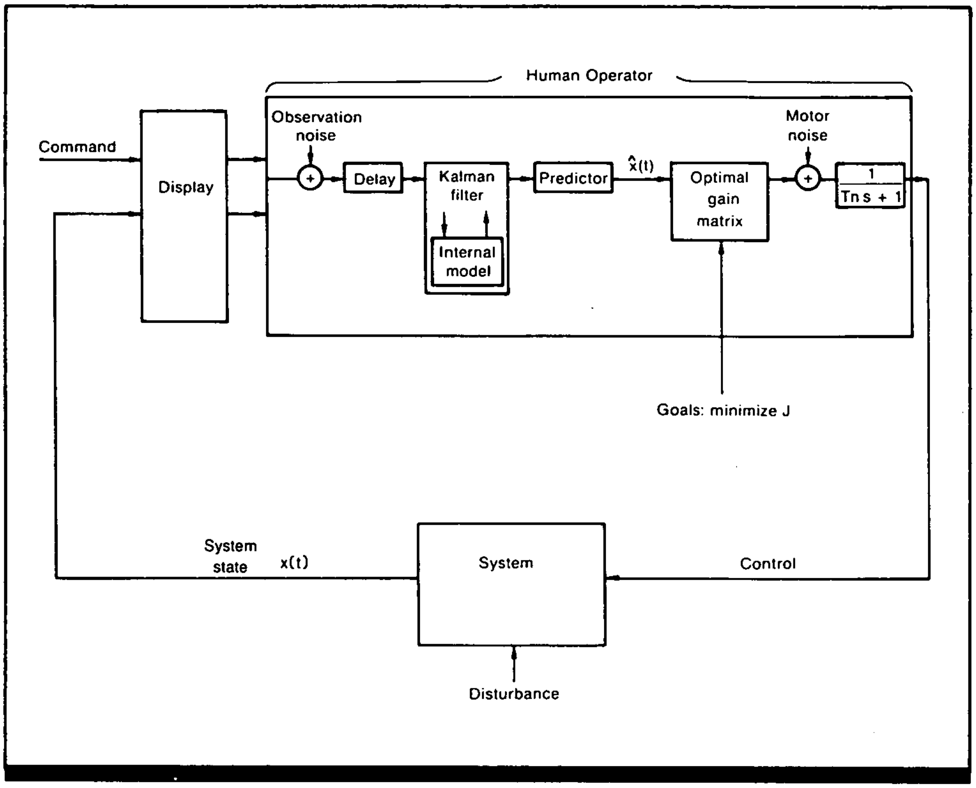

Figure 1. The optimal control model. The human operator (top) operates on the displayed vector of system information to minimize the performance criterion J. The various components of the model shown in the figure are described in the text. (From Ref. 5)

Key Terms

Bode plot; crossover model; decision making; Kalman filter; monitoring; optimization theory; process control; tracking workload

General Description

The optimal control model of a human operator is based on modern control and optimization theory. It assumes that the well-trained and well-motivated operator is "optimal" in some sense, and has an internal model of both the system and the forcing function which drives it. This model enables an estimation of system state which is limited by available perceptual data that are noisy and delayed. Further limitations include additional motor noise and a neuromuscular lag resulting in a maximum bandwidth.

In the optimal control model (shown in Fig. 1), the information from the display is corrupted by "observation noise" introduced by the human operator. This noisy representation of the display information is then delayed by an amount, τ, representing the internal human processing delay. The model then uses a Kalman filter and predictor to estimate system state. The control motion is then generated with the optimal gain matrix operating on the best estimate, $\hat{X}(t)$, of the system state, $X(t)$. The optimal gain matrix is determined by minimizing a quadratic cost functional,

$$J = E\left\{\lim_{T\to\infty}\frac{1}{T}\int_0^T\left[\sum_i q_i X_i^2 + r_i u_i^2 + g_i \dot{u}_i^2\right]dt\right\}$$

where X is the system state variable, u and $\dot{u}$ are control variables, and q, r, and g are weightings for the different variables. This reduces to

$$J = E\left\{\sum_i q_i X_i^2 + r_i u_i^2 + g_i \dot{u}_i^2\right\}$$

in the steady state.

Just as an observation noise is postulated to account for perceptual and central processing inadequacies, a motor noise is introduced to account for the human operator's inability to generate noise-free control actions. Finally, the noisy control response is smoothed by a filter that accounts for an operator bandwidth constraint. In this manner, noise is treated as an integral part of the model, rather than as an external "remnant," which is the approach used by the crossover model (CRef. 9.511).

To apply the optimal control model, the following features of the environment must be specified:

1. A linearized state variable representation of the system being controlled.
2. A stochastic or deterministic representation of the driving function of environmental disturbances to the system.
3. A linearized "display vector" summarizing the sensory information used by the operator.
4. A quantitative statement of the performance criterion or cost functional for assessing operator/machine performance.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Design of vehicle or process control systems, especially those which involve transient (step or ramp) inputs; modeling human decision making, reliability assessment, and workload; design of slowly responding and monitoring systems; design of simulations and experiments.

Empirical Validation

The model was validated in a set of manual control experiments in which experienced operators tracked systems with K, K/s, and K/s^2 dynamics in a compensatory task. **Bode plots** of the describing functions for each set of dynamics are shown in Fig. 2, where the lines represent the predicted function and the circles, squares, and triangles represent the measured data points. Figure 2a shows results when five parameters are adjusted separately for each order. The fit in Fig. 2b is only slightly worse when a single set of parameters are used for all three orders. The data show a good fit to the model (Ref. 2).

The model has also been applied with success in a number of later studies (Ref. 5).

Constraints

• The model describes the behavior of skilled operators of dynamic systems.
• The model is complex, and its use in many applications requires a large amount of computation.
• The application of the model requires considerable experience with its use.
• The model is limited to systems which can be linearized.
• The model is validated for use in continuous systems.

Key References

1. Gelb, A. (Ed.) (1974). *Applied optimal estimation*. Cambridge, MA: MIT Press.

*2. Kleinman, D. L., Baron, S., & Levison, W. H. (1970). An optimal control model of human response Part I: Theory and validation. *Automatica, 6*, 337-369.

3. Levison, W. H. (1982). The optimal control model for the human operator: Theory, validation, and applications. *Proceedings, workshop on flight testing to identify pilot workload*. (AFFTC-OTR-82-5) Edwards Air Force Base, Air Force Flight Test Center.

4. Sheridan, T. B. & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

5. Wickens, C. D. (1986). The effects of control dynamics on performance. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance*. New York: Wiley.

Cross References

9.511 Modeling of the human operator: the crossover model;

9.514 Optimal gain levels in target acquisition;

9.515 Optimal gain levels in continuous control tasks

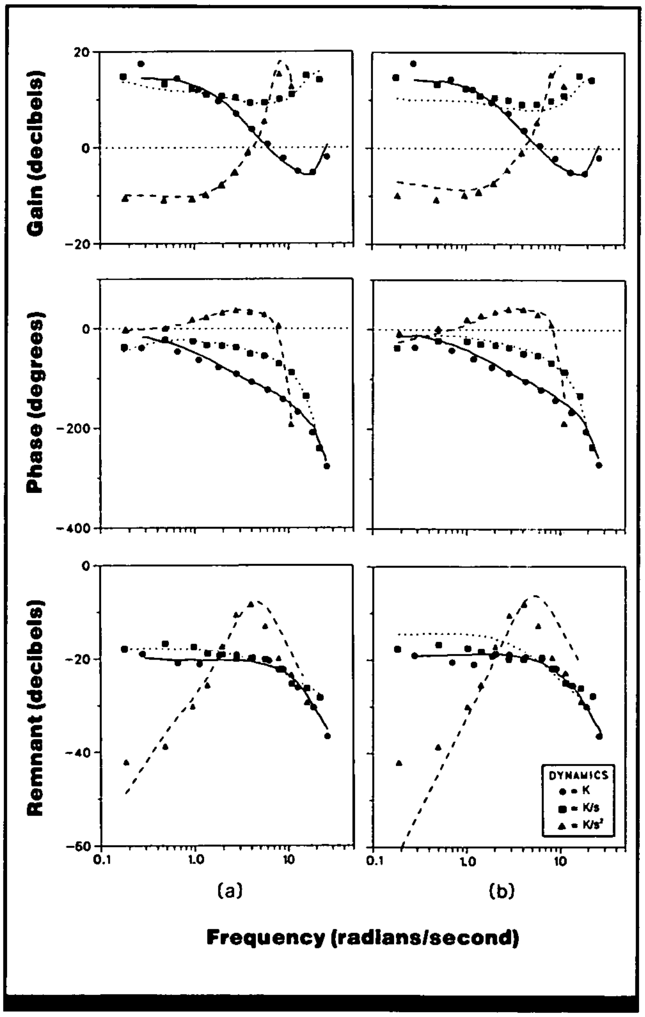

Figure 2. Bode plots and remnant spectra showing fits of the optimal control model (shown by the lines) to data points for K, K/s, and K/s^2 dynamic systems. (a) The five parameters for the model were adjusted separately for each order. (b) Same set of parameters used for all three orders. (From Ref. 5)

9.513 Display Gain

Key Terms

Display gain; open-loop gain; position control; velocity control

General Description

Display gain is the ratio of a change in display position to a change in control position. This is an open-loop gain which characterizes any system in which a human operator controls a closed-loop tracking task. Display gain is the product of two gains: the gain relating system position to control position, and the gain relating display position to system position. These gains are generally combined into a display gain because the operator doesn't usually have information on the system position; he can only see the display position.

To compare conditions across different situations, display gain is expressed in terms of the display visual angle change divided by the change in control limb angle. For systems of higher order, the display change angle must be specified in terms of the appropriate time derivative. For tasks involving isometric controls (e.g., a "force" stick), the denominator must be expressed in units of force.

Human operators can adjust their own gain upward or downward as necessary to compensate for a very broad range of values of display gain. This range of adjustment extends up to 100-fold in magnitude. This effect of gain compensation is highly consistent in aviation systems and slightly less consistent in automobile driving where reduced gains are not perfectly compensated.

Although human operators can compensate for a wide variation in display gain, this compensation can cost the operator fatigue and performance degradation. Thus there is an "optimal" display gain for best tracking performance. This gain is 0.15 for velocity control (first-order) systems and 1.5 for position control (zero-order) systems. There is also a limiting case of a very low gain such that maximum control movement is insufficient to keep the display in view, and control is lost.

Key References

1. Frost, G. (1972). Man-machine systems. In H. P. Van Cott & R. G. Kincade (Eds.), *Human engineering guide to equipment design* (Rev. ed.) (pp. 227-310). Washington, DC: U. S. Government Printing Office.

2. Gibbs, C. B. (1962). Controller design: Interaction of controlling limbs, time lags, and gains in positional and velocity systems. *Ergonomics, 5*, 385-402.

3. McRuer, D. T., & Jex, H. R. (1967). A review of quasilinear pilot models. *IEEE Transactions on Human Factors in Electronics, HFE-8*, 231-249.

Cross References

1.240 Visual angle and retinal size;

9.506 System feedback: open- and closed-loop transfer functions;

9.514 Optimal gain levels in target acquisition;

9.515 Optimal gain levels in continuous control tasks

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

9.514 Optimal Gain Levels in Target Acquisition

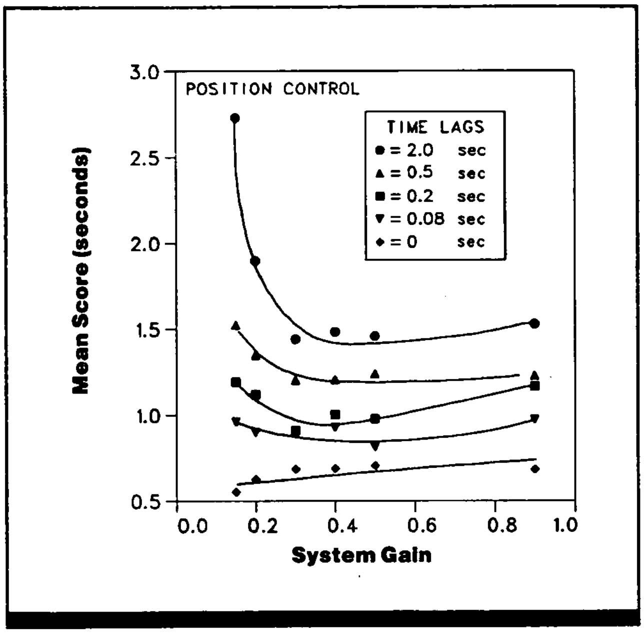

Figure 1. Hand positional control. Mean time scores with five time lags and six values of system gain (16 subjects). (From Ref. 1)

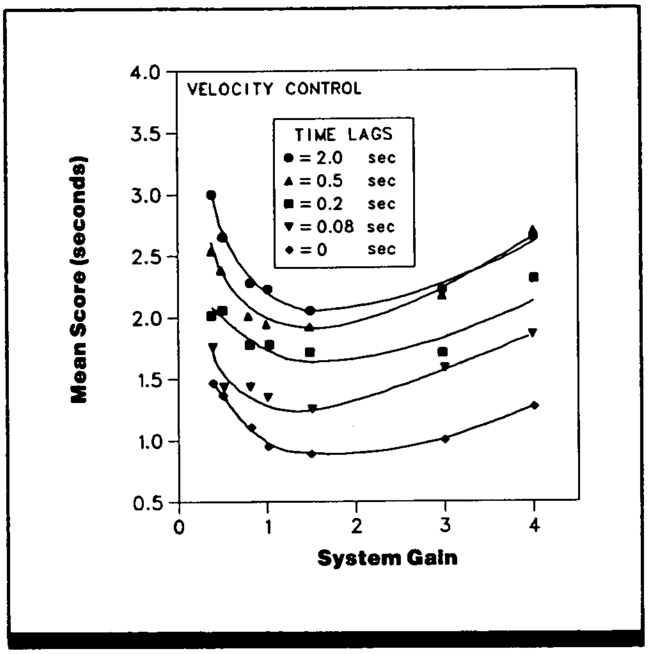

Figure 2. Hand velocity control. Mean time scores with five time lags and seven values of system gain (10 subjects). (From Ref. 1)

Key Terms

Control movements; gain; optimal control; process control; stability; step input; target acquisition; vehicle control

General Description

There is an optimal level of display gain (ratio of display movement to control movement) in any target acquisition task. It is a compromise between optimizing the initial acquisition phase of the control movement, where high gain is helpful in fast acquisition, and the final "steadying time" phase, where lower gains are better. The resulting optimal gain level is usually a moderate one for the task.

Applications

Choice of optimal display **gain** for vehicle or process control target acquisition task.

Methods

Test Conditions

- **Position control (zero order dynamics) used in Figs. 1 & 3, velocity control (first order dynamics)** in Fig. 2.
- One-dimensional movement of a cursor on a CRT controlled by a joystick for Figs. 1 & 2; movement of a pointer on a dial controlled by a rotating knob for Fig. 3.

Experimental Procedure

- Independent variables: display gain, defined as visual angle displacement of the cursor divided by angular deflection of the control stick (both in the same unit— radians or degrees) for Fig. 1; radians per second for Fig. 2; inches of display movement per revolution of knob for Fig. 3; time constant of the exponential lag (time it takes for output to reach 63% of its final value) for Figs. 1 & 2; target tolerance and distance travelled for Fig. 3
- Dependent variable: target acquisition time in seconds for all three figures
- Observer's task: move a cursor or pointer a set distance in response to a step input
- Observer characteristics not specified

Experimental Results

- Target acquisition performance is best at moderate gain levels.
- Very high gains give poor results because of the difficulty in making precise movements, even though initial acquisition is more rapid.
- Lower gains allow precise movement, but require a longer initial acquisition time.
- At the very lowest gains, performance deteriorates rapidly.
- The effect of gain changes on performance is relatively flat over a fairly wide range of conditions, especially for position control.
- If lags are inevitable in the control dynamics, they may be partially compensated for by higher gains, as long as this does not produce system instability.

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Constraints

- Only position and velocity control were studied.
- Results may be somewhat different for a continuous control task than for a target acquisition task.

Key References

*1. Gibbs, C. B. (1962). Controller design: Interactions of controlling limbs, time lags, and gains in positional and velocity systems. *Ergonomics, 5*, 385-402.

*2. Jenkins, W. L., & Olson, M. W. (1952). The use of levers in making settings on a linear scale. *Journal of Applied Psychology, 36*, 269-271.

Cross References

7.614 Factors affecting target acquisition on television;

9.502 Response of a gain element with pure time delay;

9.504 Bode plot representation of a gain element with pure time delay;

9.515 Optimal gain levels in continous control tasks;

Handbook of perception and human performance, Ch. 39, Sect. 2.1

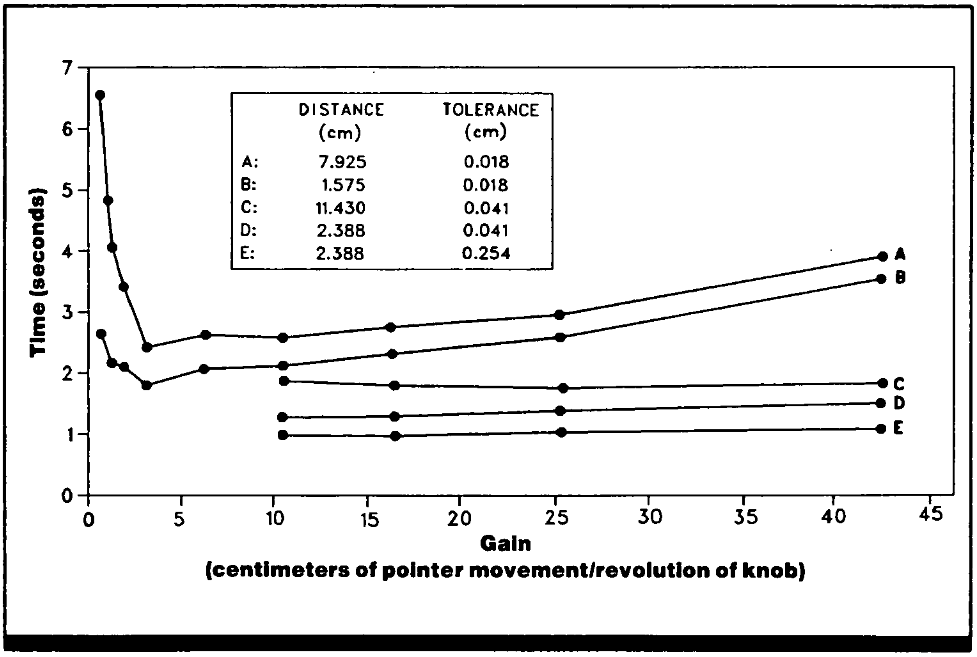

Figure 3. The optimal level of gain for a zero-order rotational control in a target acquisition task. Gain (express in centimeters of display movement per revolution of knob) is shown on the horizontal axis. Target acquisition time is on the vertical axis. The five curves depict different degrees of target tolerance and distance traveled. As the tolerance is less (curves A and B), performance is hurt more by high gains. (From *Handbook of perception and human performance*, adapted from Ref. 2)

9.515 Optimal Gain Levels in Continuous Control Tasks

Key Terms

Compensatory displays; control gain; control loading; Cooper-Harper rating; gain; phase margin; pilot ratings

General Description

Display gain in a tracking system is the ratio of display movement to control movement. If the operator must continually make large control motions to achieve relatively small display motions (a low-gain system), fatigue will result. If a small control motion produces a large display motion (a high-gain system), the system will have a lower phase margin and poorer performance due to potential instability. Thus, there is an optimum level of gain for a given system, as is shown in Figs. 1, 2, and 3; this level is lowered by reducing control effort (e.g., reducing stick spring loading) and raised by making stability easier to achieve (e.g., minimizing phase lag and time delays).

Applications

Design of any dynamic control system where gain may be varied (e.g., the turn ratio of an automobile steering wheel).

Methods (Ref. 2)

Test Conditions

- Data obtained in a fixed-base fighter cockpit simulator with a two-gun CRT display
- **Transfer functions** for a series of experiments generated by analog computer
- Simulated random input comprised of ten equal-amplitude sine waves of frequencies from 0.1-1.0 radians/sec
- Display was compensatory and "inside out" (CRefs. 9.528, 9.529)

Experimental Procedure

- Independent variables: system gain; system transfer functions were also varied
- Dependent variables: average absolute error, average absolute control deflection, pilot opinion ratings on the **Cooper-Harper** ratings scale
- Subject's task: keep a vertically moving error dot on stationary cross-hairs
- Five pilot instructors with experience

Experimental Results

- Tracking performance decreases only slightly as system gain increases, because operators adjust their gain to system gain (Fig. 1a). The cost associated with this adjustment leads to optimum gain level ratings.
- Average force applied to a control stick decreases as the system gain increases (Fig. 1b).
- Pilot opinion ratings consistently show that there is an optimum gain level (neither too high nor too low) for a given system (Fig. 1c). The optimum level depends on the characteristics of the system.

Repeatability/Comparison with Other Studies

Figures 2 and 3 indicate similar findings for pilot opinion ratings.

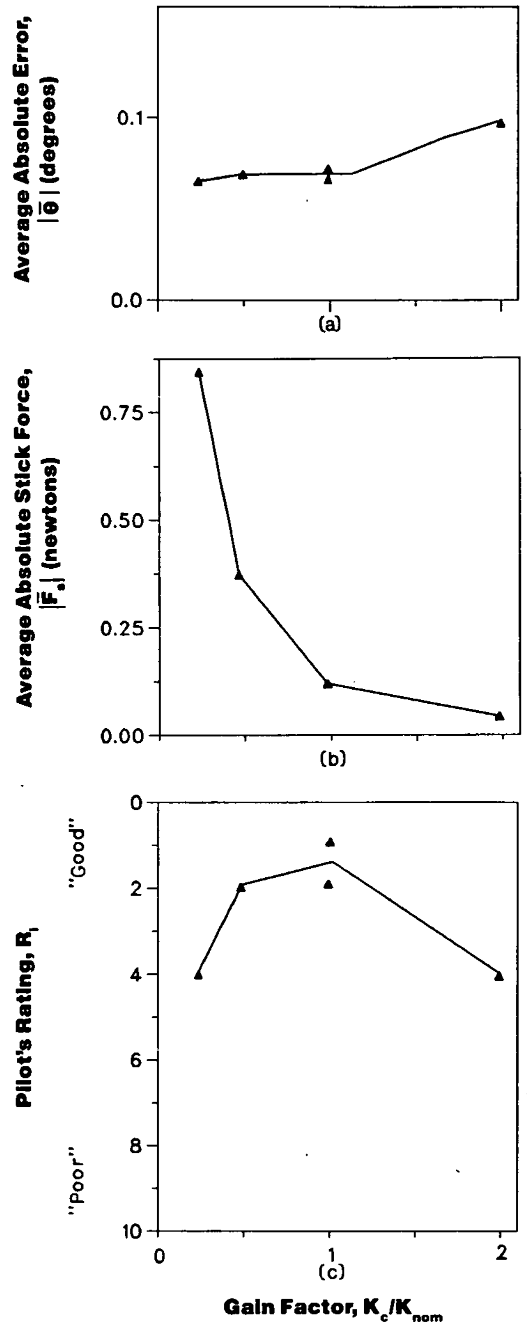

Figure 1. (a) Tracking error, (b) stick force, and (c) pilot ratings as a function of gain for a "good" system. (From *Handbook of perception and human performance*, adapted from Ref. 2)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

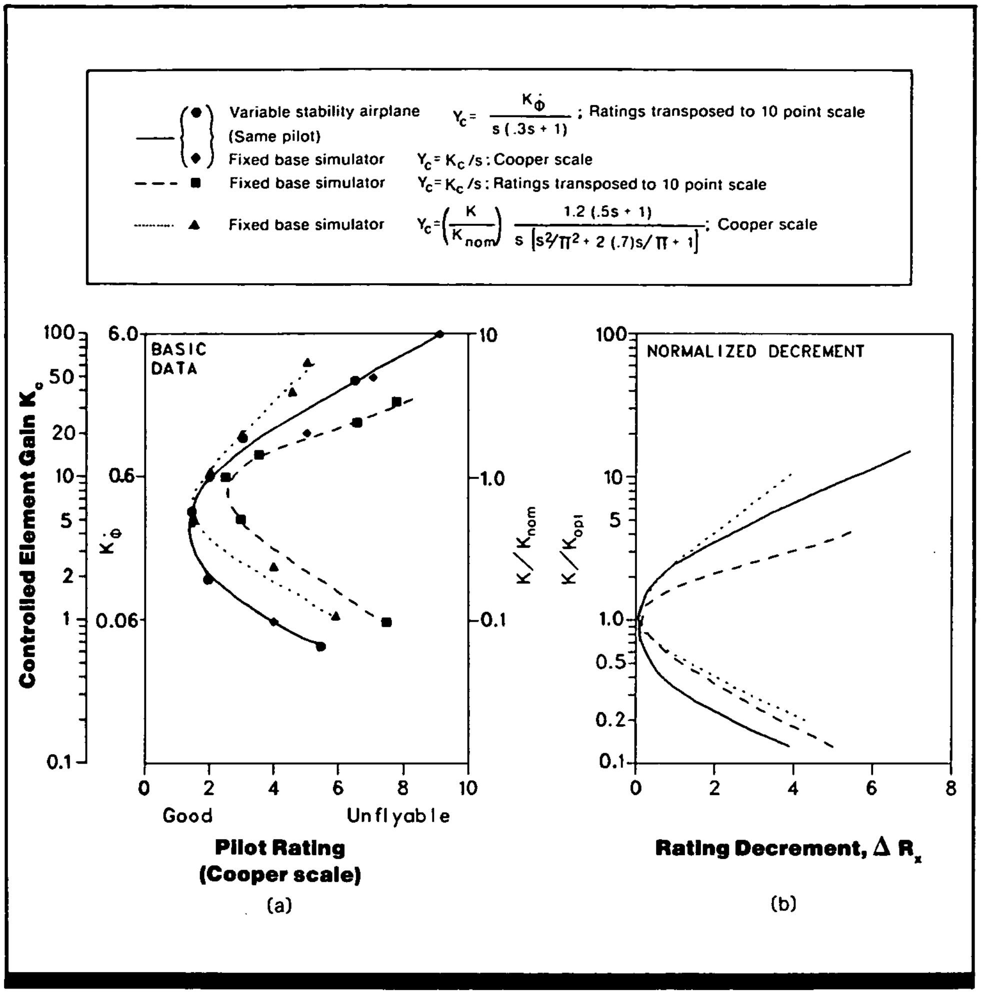

Figure 2. Pilot ratings for systems with different dynamic elements (across several studies); gain is plotted as a function of pilot ratings and shows an optimal gain level for each system. (a) The raw data, and (b) the data after normalization around the optimal gain level. (From D. T. McRuer & H. R. Jex, A review of quasi-linear pilot models, *IEEE Transactions on Human Factors in Electronics, HFE-8*. Copyright © 1967 IEEE. Reprinted with permission.)

Constraints

- Optimum gain levels can cover a fairly broad range of gains for a system, as shown in Fig. 2. However, a wide departure leads to severe decrements in pilot ratings.
- The optimum gain level cannot be predicted from knowledge about a system; it must be empirically determined.

Key References

1. Hess, R. A. (1973). Nonadjectival ratings scales in human response experiments. *Human Factors, 15*, 275-280.

*2. Jex, H. R., & Cromwell, C. H., III. (1961). *Theoretical and experimental investigation of new longitudinal handling quality parameters* (ASD-TDR-61-26). Wright-Patterson Air Force Base, OH: Aeronautical Systems Division. (DTIC No. AD282878)

*3. McRuer, D. T., & Jex, H. R. (1967). A review of quasilinear pilot models. *IEEE Transactions on Human Factors in Electronics, HFE-8*, 231-249.

4. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

Cross References

9.528 Pursuit versus compensatory displays;

9.529 Inside-out versus outside-in displays;

Handbook of perception and human performance, Ch. 39, Sect. 2.1

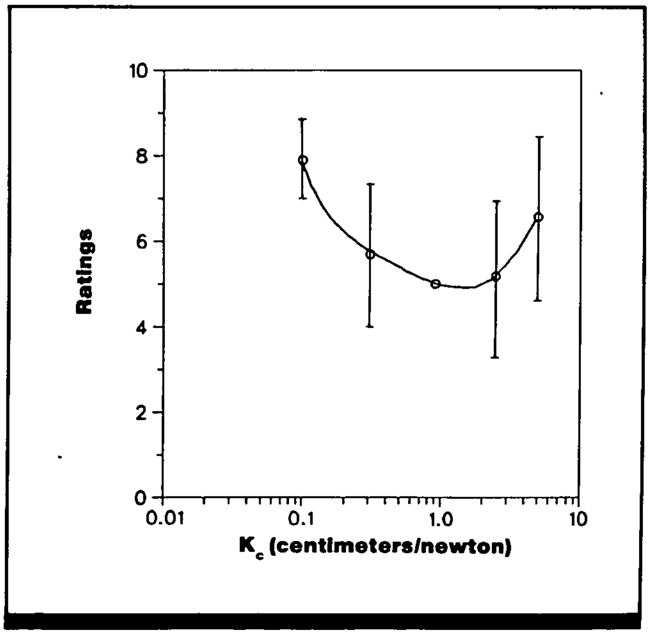

Figure 3. Pilot ratings for tracking an unstable element as a function of gain (expressed in terms of centimeters of display movement/newton of stick force). (From Ref. 1)

9.516 Effect of Transmission Lag (Pure Time Delay) in Continuous Tracking with Zero-Order Dynamics

Key Terms

Compensatory tracking; control lag; pursuit eye movements; time on target; tracking

General Description

In systems with **transmission lags** (also called pure time delay), control movements are reproduced perfectly, but after some fixed time delay. As the time delay increases, human control of a zero-order dynamic system (CRef. 9.528) decreases. Delays as brief as 40 msec affect performance, even if the delay is not detected by the human operator (e.g., the experimental subject). The effect is greater for higher input frequencies and for higher order systems.

Applications

Vehicle control, especially aircraft attitude; process control systems; any dynamic system in which there is a time delay between the operation of a control and its effect.

Methods

Test Conditions

• Target was inked line from recording oscillograph with paper moving at 125 mm/sec; subject viewed line through 2-mm slit that could be moved to change length of delay between subject's response and when subject saw the results of the response
• Sine-wave input frequency: combined 0.10 and 0.50 Hz for Exp. 1; simple sine waves of 0.20 Hz for Exp. 2 and 0.10 Hz for Exp. 3
• Delay intervals of 0, 40, 80, 160, or 320 msec for Exp. 1; 0, 80, or 160 msec for Exp. 2; 0, 80, or 320 msec for Exp. 3
• 30-sec practice trial and then 30 sec of recorded tracking for each delay interval

Experimental Procedure

• Independent variables: delay interval, input frequency
• Dependent variable: time on target
• Subject's task: adjust the indicator position to a fixed center-reference position by rotating a control knob
• 25 male employees of the Aero Medical Laboratory in Exp. 1 and 10 employees in Exps. 2 and 3

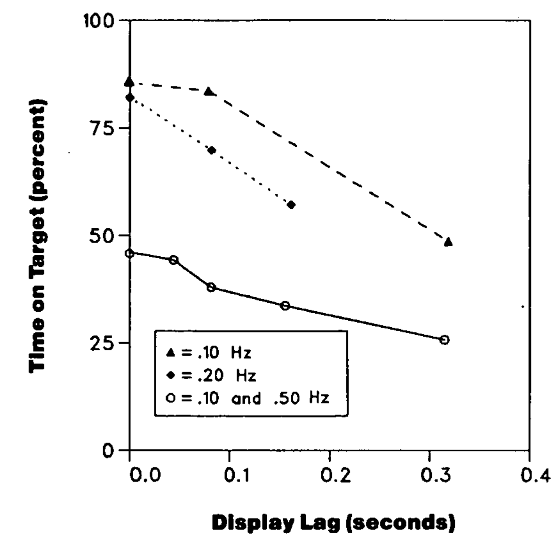

Figure 1. Time on target in a tracking task as a function of display lag for three different sine-wave inputs. (From *Handbook of perception and human performance*, after Ref. 3)

Experimental Results

• Any **transmission lag** in a system, no matter how short, will adversely affect tracking accuracy.
• Time on target decreases at a constant rate with increasing transmission lag. The effect is found even when the human operator does not detect the lag.

Variability

Standard errors of means were quite low, ranging from 0.25 in Exp. 1 to 1.14 in Exp. 2 for means of ~7-24 sec.

Repeatability/Comparison with Other Studies

Several studies have replicated the findings reported.

Constraints

• Error will probably increase for higher-order systems.
• Results are probably applicable only to systems with transmission-type control lags.
• Lags in the experimental system were in slight error whenever the moving pen was not on exact center.
• The input to the subject is partially dependent on the subject's own responses; if behavior changes as lag changes, display motion also changes (this is true of most compensatory tracking tasks).
• This type of pure transmission lag is unusual; it could result from controlling a remote space vehicle from the earth; in most cases, control movement initiates indicator movement immediately, but the full effect is not reached for some time (CRef. 9.518).
• The performance measure used, time-on-target, is rather crude, although it is unlikely that more sophisticated measures, such as integrated error (CRef. 9.510) would yield markedly different results.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

2. Wallach, H. C. (1961). *Performance of a pursuit tracking task with different delay times inserted between the control mechanism and display cursor* (TM-12-61). Aberdeen Proving Ground, MD: Human Engineering Laboratories. (DTIC No. AD263734)

*3. Warrick, M. J. (1949). *Effect of transmission-type control lags on tracking accuracy* (AF-TR-5916). Wright-Patterson AFB, OH: Air Materiel Command. (DTIC No. AD630292)

Cross References

9.510 Error, system control criteria, and human limitations in error control;

9.518 Joint effects of first-order exponential lag and gain on target tracking performance;

9.528 Pursuit versus compensatory displays;

Handbook of perception and human performance, Ch. 39, Sect. 2.2

9.517 Temporal Mismatch of Motion and Visual Displays: Effect on Continuous Tracking with Simulated Aircraft Dynamics

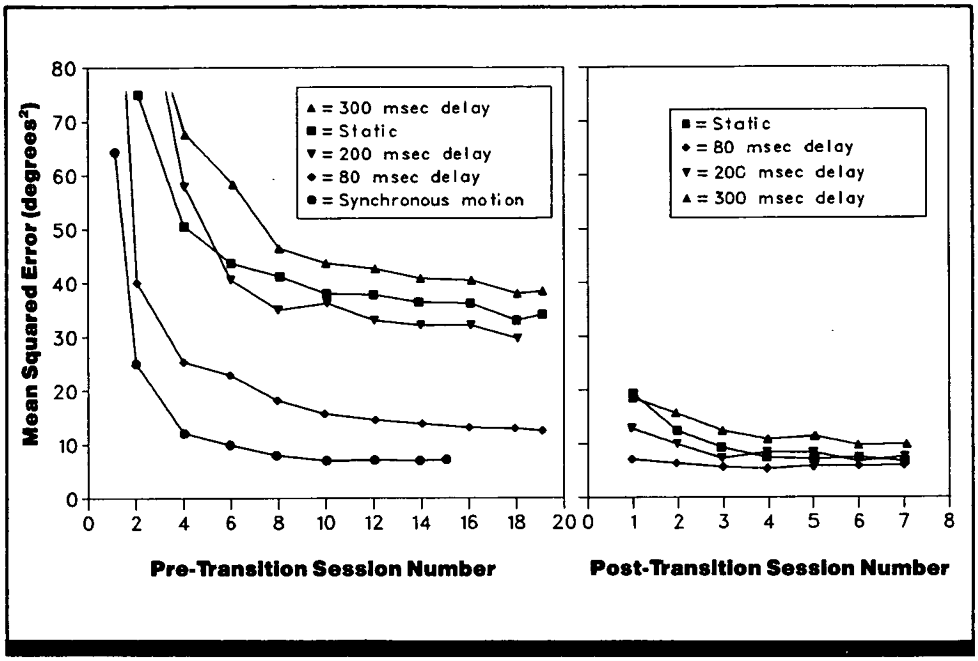

Figure 1. Differences in mean squared error for a continuous tracking task as a function of amount (session number) and type of (curve parameter) initial training. Delay indicates motion cues followed visual cues by the specified number of milliseconds. Plots are for (a) all initial-training conditions (experimental and synchronous control) and (b) final synchronous-cue (0 lag) condition for all experimental subjects. (From *Handbook of perception and human performance*, adapted from Ref. 1)

Key Terms

Inside-out displays; phase lag; practice; proprioception; simulator motion; tracking; training; transfer of training

General Description

The introduction of a time delay in system response generally produces a decrement in tracking performance. This is true for delays that may be encountered with limited computer processing speed for visual displays, even when operators are unaware of the delay. Delays as short as 80 msec produce noticeable performance decrements, and also impede later learning in situations with no delay (CRefs. 9.504, 9.516).

Applications

System design with delays between operator input and display output; control of remote piloted vehicles or space systems; updating of systems with faster computers; sluggish systems.

Methods

Test Conditions

- Operators tracked **roll angle** in aircraft simulator using an **inside-out display** (CRef. 9.529) of a 3.2-cm (1.25-in.) rotating line superimposed on stationary horizontal and vertical lines; display on ~23-cm television monitor
- Simulated aircraft dynamics of

$$\frac{\phi(s)}{U(s)} = \frac{14}{s} \cdot \frac{5}{s+5} \cdot \frac{19}{(s+19)}$$

where $\phi(s)$ is roll angle in degrees, and $U(s)$ is control force in pounds; complex disturbance input also added
- Initial training condition (to asymptote) of synchronous motion and visual cues (control group), 80-, 200-, or 300-msec delay for visual cues, or visual cues only; experimental groups then transferred to synchronous-cue condition for training to asymptote in that condition

Experimental Procedure

- Independent variables: initial training, experimental condition, session number (amount of training)
- Dependent variable: mean squared error
- Observer's task: maintain wings of simulated aircraft in level position when buffeted by random turbulence (control the roll angle of the display with a side-mounted control stick)
- 4-5 college students with no practice in each experimental condition

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

• Experimental conditions with delay lead to significant degradations in performance (e.g., mean squared error after 14 sessions increases from 7.5 deg^2 for the synchronous condition to 40 deg^2 for the 300-msec delay condition).
• Performance with motion cues is better than static performance for delays up to 200 msec, but not for 300-msec delays.
• Transfer of training to the synchronous condition is accelerated by the 80- and 200-msec training (compared to the static and 300-msec training). Thus, training in the simulator, even with delays of up to 200 msec, aids transfer to the aircraft (synchronous) condition more than training in the static condition.

Variability

Individual differences were high early in training, but decreased at asymptotic performance level.

Constraints

• Results are tentative, because only small subset of data was fully analyzed.
• The degradation in performance caused by time delays may not occur in a system with totally predictable motion.
• Delays of up to 300 msec cause measurable decrements in performance; longer delays may result in system instability rather than larger measurable decrements in performance.

Key References

*1. Levison, W. H., Lancraft, R. E., & Junker, A. M. (1979). Effects of simulator delays on performance and learning in a roll-axis tracking task. *Proceedings of the Fifteenth Annual Conference on Manual Control* (AFFDL-TR-793134). Wright-Patterson Air Force Base, OH: Air Force Flight Dynamics Laboratory. (DTIC No. ADA080563)

Cross References

9.504 Bode plot representation of a gain element with pure time delay;

9.516 Effect of transmission lag (pure time delay) in continuous tracking with zero-order dynamics;

9.529 Inside-out versus outside-in displays;

Handbook of perception and human performance, Ch. 39, Sect. 2.2

9.518 Joint Effects of First-Order Exponential Lag and Gain on Target Tracking Performance

Key Terms

Controls; gain; target acquisition; time constant; time-on-target; tracking

General Description

A system with a first-order lag has behavior that is intermediate between a position control (zero-order) system and a velocity control (first-order) system. A first-order lag with a very short time constant is like position control, while a lag with a very long time constant is like velocity control. Moderate time constants give intermediate behavior.

The effect of the lag time constant on human performance interacts with the effect of display gain. At low values of gain, increasing the time constant tends to deteriorate performance. However, at higher gain increasing the time constant improves performance up to a point. This is probably because the lag causes a reduced magnitude in the bandwidth of interest, which is compensated for by the higher gain.

Applications

Design of controls for vehicle and process control.

Methods

Test Conditions

- Two-dimensional compensatory tracking; target was fluorescent spot on CRT ~28 cm from subject; target was controlled by joystick movement
- Zero-order dynamics (position control) with first-order lag of variable time constant
- Control/display ratios (gain) ranged from 3-30; time constants ranged from 0.3-3 sec
- Input signal contained a sum of 3 sinewaves from 0.05 Hz to 0.18 Hz.

Experimental Procedure

- Independent variables: time constant, gain
- Dependent variable: time on target
- Subject's task: move the joystick and keep the spot within a 0.95-cm (3/8-in.) square target area
- 8 subjects, 7 right- and 1 left-handed male adults with extensive practice

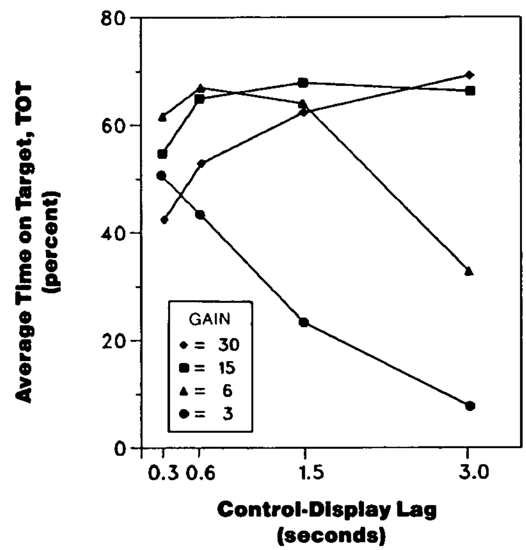

Figure 1. The joint effects of exponential lag and gain on time-on-target in a compensatory tracking task. (From *Handbook of perception and human performance*, adapted from Ref. 1)

Experimental Results

- At a display/control ratio of 3 (low gain), average percent time-on-target decreases from just over 50% to below 10% as the exponential lag increases from 0.3-3.0 sec.
- For a display/control ratio of 6, the time-on-target shows a peak at a time constant of 0.6 sec., with lower performance at both shorter and longer time constants.
- At the higher gain levels of 15 and 30, time-on-target improves with increasing time constant and stays high even at the longest time constant.
- In summary, the introduction of a first order lag generally improves performance when gain is high, but hurts performance when gain is low.

Variability

An analysis of variance was used; mean square errors were not reported.

Constraints

- These results were obtained using average percent time-on-target as a measure of performance. This measure is generally considered a poorer indicator than the more common integrated error measure (e.g., it may not reflect incipient system instability). The general findings with respect to the joint effects of gain and lag would probably be the same, but the magnitude of the effects might differ.
- The findings relate only to position (and perhaps rate) control. If lag is added to a higher-order system, the effect is generally detrimental to performance.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Rockway, M. R. (1954). *The effect of variations in control-display ratio and exponential time delay on tracking performance* (ASD-TR-54-618). Wright-Patterson Air Force Base, OH: Aeronautical Systems Division. (DTIC NO. AD062763).

2. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

Cross References

9.510 Error, system control criteria, and human limitations in error control;

9.513 Display gain;

Handbook of perception and human performance, Ch. 39, Sect. 2.2

9.519 Control Order

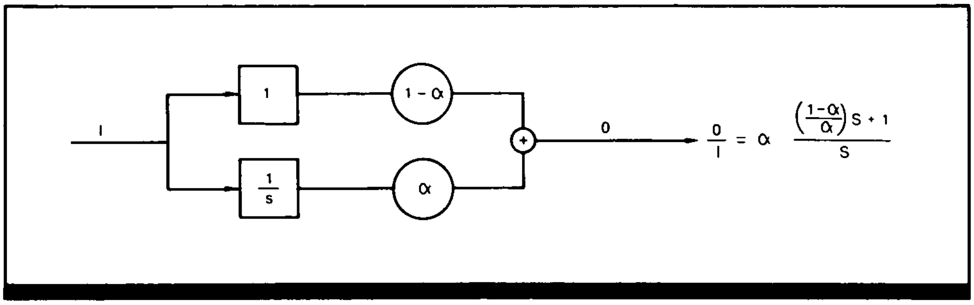

Figure 1. A zero-order system and first-order system coupled to produce an intermediate system. (From *Handbook of perception and human performance*)

Key Terms

Bode plot; gain; Laplace operator; phase lag; system stability; tracking

General Description

Perhaps the most important variable that determines the stability and accuracy of human tracking performance is the order of the control system being tracked. Control system order can be described by the variables K and s, with K as the gain of the system and s as the **Laplace operator**, a representation of a continuous signal that accounts for both frequency-domain and time-domain characteristics. Humans can normally track control system orders spanning the range from Ks through K (**position control**), K/s (**velocity control**), K/s^2 (acceleration control) to K/s^3.

Although these control system orders are discrete, intermediate points between them may be generated by adding a **first-order** lag (a gradual "homing in" on the final value) and varying its time constant (the time it takes to reach 63% of its final value). This intermediate system changes from lower order at low frequencies to higher order at high frequencies at the break frequency in the **Bode plot** (CRef. 9.518). Because the lag time constant is inversely proportional to the break frequency, a shorter time constant means a higher break frequency. Thus, the shorter the time constant, the greater the frequency range over which the system acts at the lower order.

Intermediate points between control system orders can also be generated by adding the output of lower- and higher-order systems in proportion so that system order increases as the proportion of the higher order system is increased. Such a system is shown in Fig. 1, where a zero-order and a first-order system are shown coupled to produce an intermediate system. The gain of the lower-order system (a zero-order system in this case) is weighted by α, and that of the higher-order system by $1-\alpha$. The ratio of these two gains, $\alpha/(1-\alpha)$ is a lead time constant which then defines the break frequency of transitioning from a lower- to a higher-order system.

The behavior of these two methods of obtaining intermediate control system orders is illustrated with the amplitude portion of a Bode plot, showing amplitude ratio as a function of frequency (Fig.2). The top functions show long and short lead time constants (second method), and the bottom functions show short and long lag time constants (first method). The functions of the left show two systems that behave in an essentially zero-order fashion, with the amplitude ratio remaining constant over a wide range of input frequencies. They have long lead (T_L) or short lag (T_l) time constants. The functions on the right show systems that behave in a first-order fashion, in which amplitude ratio goes down as frequency goes up. They have short lead or long lag time constants.

Applications

Design of control systems, usually for vehicles; some process control systems may also involve higher control orders.

Constraints

- Extreme values of gain, lag, or input frequency may lead to system instability.
- The higher the system order, the greater the workload imposed on a human operator of the system, and the more likely the system is to become unstable.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

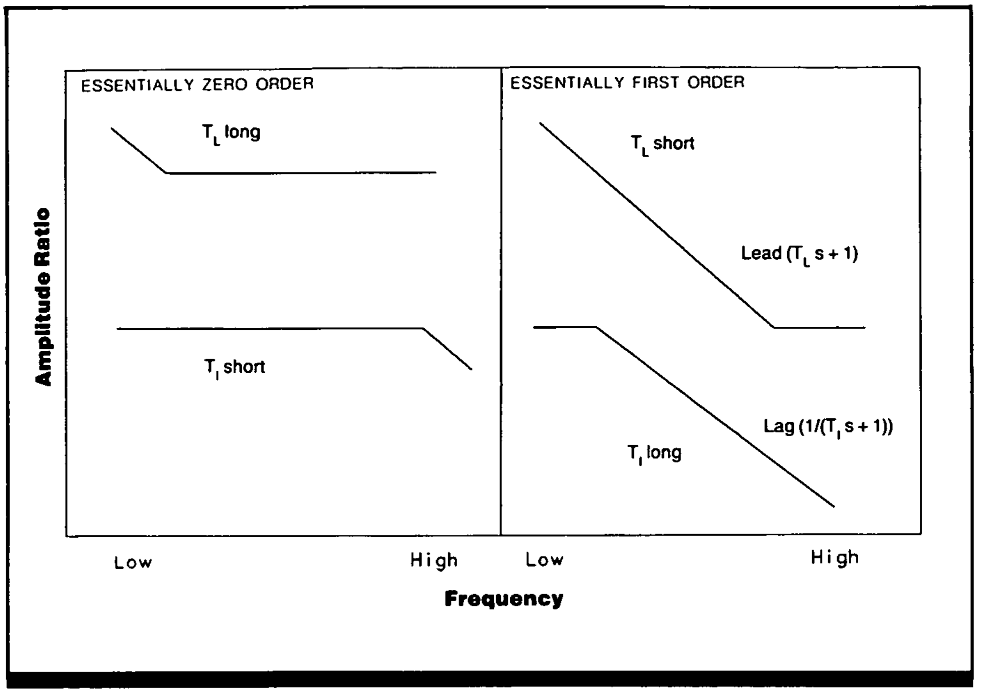

Figure 2. Amplitude section of a Bode plot showing amplitude ratio as a function of frequency for transfer functions with different lead and lag time constants. (From *Handbook of perception and human performance*)

Key References

1. D'Azzo, J. J., & Houpis, C. H. (1966). *Feedback control systems analysis and synthesis*. New York: McGraw-Hill.

2. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

Cross References

9.507 Phase margin: a measure of stability;

9.518 Joint effects of first-order exponential lag and gain on target tracking performance;

Handbook of perception and human performance, Ch. 39, Sect. 2.3

9.520 Effects of System Order and Aiding on Tracking Performance

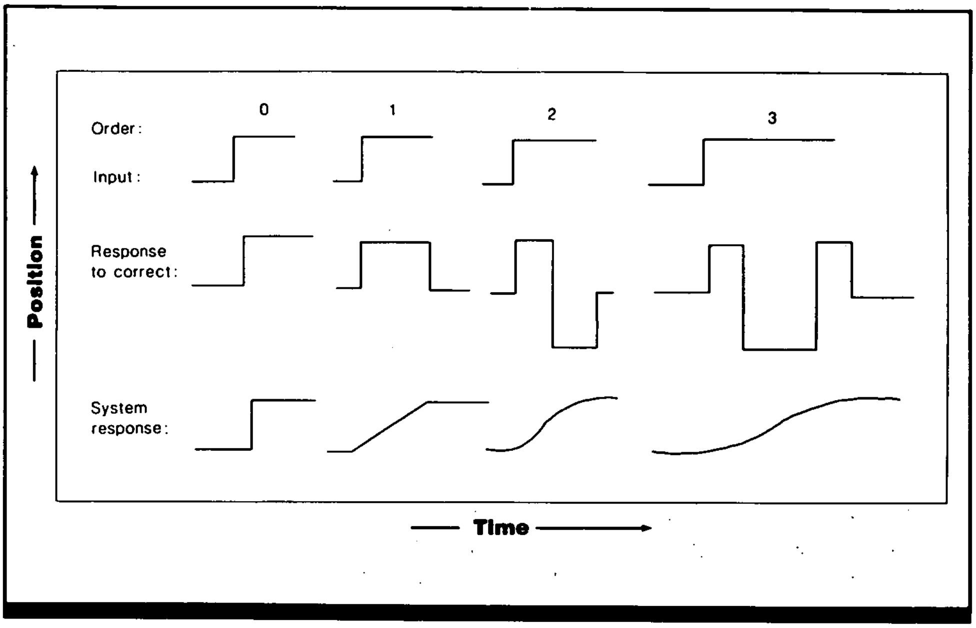

Figure 1. Inputs, required operator responses, and subsequent system responses to a step input for zero-, first-, second-, and third-order systems, with position as a function of time. (From *Handbook of perception and human performance*)

Key Terms

Control aiding; control placement; system order; tracking

General Description

System control order (CRef. 9.519) is probably the most important determinant of human tracking performance. As system control order increases, the demands on the human operator become more complex. Consequently, target acquisition (response to a step input) performance declines monotonically with increasing system order.

The primary reason for the decrease in performance is the number of operator inputs required to compensate for a step input in systems of zero, first, second, and third order. In a zero-order (position control) system, the operator simply moves the control to the desired new position. In a first-order system, where the operator's control movement results in a fixed rate of movement of the system output, two control motions are required: one to begin an output rate and a second, opposite motion to stop it. This increasing complexity continues for each higher control order.

The situation with a ramp input is slightly different; the operator must compensate for both a change in position and a change in rate. Thus a first-order (rate control) system offers some advantage in that a constant control deflection will produce a constant rate of movement; consequently, the operator does not have to match control velocity to target velocity. However, the two responses necessary for a step input must still be made.

The outputs of zero-order (position) and first-order (rate or velocity) control may be linearly combined, so that a single operator input affects both the position and velocity of the system response. This is called aiding or rate-aiding, and the proportion of position and velocity terms may be varied and expressed as the aiding time constant (the ratio of position to velocity component) (CRef. 9.521).

The optimum value of the aiding time constant depends on the particular task. Performance on tasks that require continuous velocity tracking, especially at high velocities, will benefit from more velocity control (i.e., aiding with a lower time constant). Conversely, performance on tasks that involve many frequent position corrections will benefit from more position control (i.e., aiding with a higher time constant). Aiding that increases the control order of the system is sometimes called unburdening. Other types of aiding may decrease the system control order; this is especially useful when applied to second- and third-order systems.

Performance in tracking random inputs varies little between zero- and first-order systems because of the tradeoff between position matching and velocity matching. However, tracking performance falls off dramatically for higher-order systems. In going from a first- to a second-order system (velocity to acceleration control), root-mean-square tracking error increases from 40-100%, regardless of variations in input, displays, and task loading.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

The position of a system on the continuum between zero- and first-order systems may be varied by changing the lag time constant of an exponential lag; then the time constant for optimum performance is a function of the system gain (CRef. 9.518). Position on the continuum may also be varied by changing the lead time constant in a rate-aided system (CRef. 9.521) then optimum performance generally is obtained at moderate lead time constants (about 0.5 sec).

Key References

*1. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, Mass: MIT Press.

Cross References

9.518 Joint effects of first-order exponential lag and gain on target tracking performance;

9.519 Control order;

9.521 Effects of control aiding, input frequency, and display type on tracking of a random input;

Handbook of perception and human performance, Ch. 39, Sect. 2.3

9.521 Effects of Control Aiding, Input Frequency, and Display Type on Tracking of a Random Input

Key Terms

Compensatory tracking; control aiding; pursuit eye movements; simulation; tracking

General Description

Performance on a tracking task, as measured by **integrated error** (CRef. 9.510), does not differ greatly for **zero-order (position control)** and **first-order (rate control)** systems. This is true for both pursuit (both target and cursor positions are displayed) and compensatory (only the difference between target and cursor positions is displayed as error) tracking tasks (CRef. 9.528).

Position of a tracking system on a continuum between zero and first-order control can be varied by introducing a **rate-aiding** lead time constant (CRef. 9.520). With increases in input frequency, error increases for all systems tested. In addition, control order interacts with frequency, with position control being worst for lower frequencies, and rate control being worst for higher frequencies. However, for the entire range of frequencies tested, the intermediate time constant was best overall.

Applications

Design of vehicle controls; design of process controls such as for a chemical plant process flow; design of simulators for vehicle control.

Methods

Test Conditions

- Point target moved horizontally on an oscilloscope in either pursuit or a compensatory display mode; three simulated random courses, each a complex of three sine waves with sine-wave ranges of 0.04-0.11 Hz for Course A, 0.11-0.28 Hz for B, and 0.28-0.44 Hz for C
- Control dynamics were pure position control, rate-aided with 0.5 sec time lead, or pure rate control

Experimental Procedure

- Independent variables: display mode, input frequency, type of system dynamics
- Dependent variable: integrated error in arbitrary units
- Subject's task: track target on oscilloscope screen
- 6 Naval enlisted men per course, with extensive practice (18 total)

Experimental Results

- The integrated-error score increases (i.e., performance is poorer) as input frequency increases.
- Performance with the pursuit display is generally better ($p < 0.01$), except the compensatory display is better for the higher-order systems at low frequencies (Course A) ($p < 0.01$).
- For Course A, position control is worst; rate is slightly worse than rate-aided control for pursuit displays ($p < 0.001$) but not significant for compensatory displays.
- For Course B (middle frequencies), rate control is worst; rate-aided and position control are equivalent.
- For Course C (higher frequencies), rate control is worst; rate-aided is slightly worse than position control for pursuit ($p < 0.01$) and compensatory ($p < 0.05$) displays.

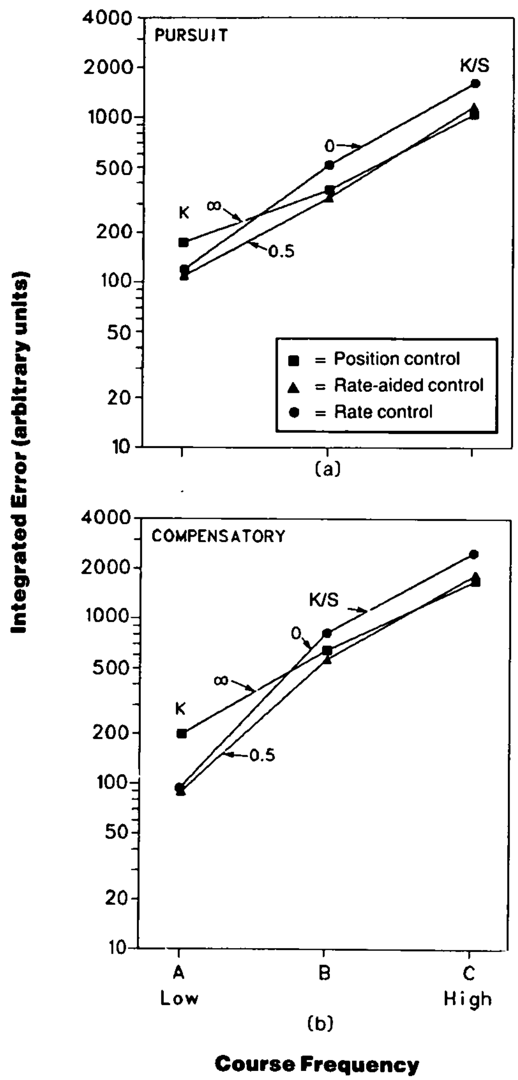

Figure 1. Error in a tracking task as a function of input (course) frequency and system dynamics for (a) a pursuit display and (b) a compensatory display. *K* indicates a position control system (i.e., with an aiding time constant of infinity) and *K/S* indicates a rate control system (i.e., with an aiding time constant of zero). The aiding time constant for the third system equalled 0.5 sec (i.e., control displacement yielded both a position displacement equivalent to that for the position control system and a rate change equivalent to that for the rate control system. (From Ref. 1)

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The findings are similar, though not directly comparable, to those found in many later studies. Nonparametric Wilcoxon tests were used to compare data points because of lack of homogeneity of variance for Course A.

Constraints

- Course frequencies are on the low end of those which can be successfully tracked.
- Integrated error is only one, though probably the best, measure of tracking performance.
- Only zero- to- first-order systems were employed. Results for higher-order systems would be markedly different, with much higher integrated error scores.

Key References

*1. Chernikoff, R., & Taylor, F. V. (1957). Effects of course frequency and aided time constant on pursuit and compensatory tracking. *Journal of Experimental Psychology, 53,* 285-292.

2. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems.* Cambridge, MA: MIT Press.

Cross References

9.510 Error, system control criteria, and human limitations in error control;

9.518 Joint effects of first-order exponential lag and gain on target tracking performance;

9.519 Control order;

9.520 Effects of system order and aiding on tracking performance;

9.528 Pursuit versus compensatory displays;

Handbook of perception and human performance, Ch. 39, Sect. 2.3

9.522 Effect of System Lag on Perceived Task Difficulty

Key Terms

Bank angle control; Cooper-Harper rating; lag time constant; lead time constant; roll control; task difficulty; workload

General Description

As the **lead time constant** T_L for a tracking task increases (that is, the pilot must allow a longer lead time to compensate for system lag), the pilots have a monotonically lower opinion rating of the task. In other words, they consider tracking more difficult with longer system lags. (The plot in Fig. 1 shows the decrease in opinion ratings as an increase in rating decrements.)

Applications

Design of aircraft controls, especially bank angle control; possible applications in some process control problems.

Methods

Test Conditions

- Data derived from a number of reports
- Some data from missions in many types of aircraft (fighters, heavy bombers and transports, helicopters, vertical takeoff and landing, and commercial aircraft)
- Some data from simulator studies with various imposed conditions
- All studies involved aircraft roll control
- Data collected after a mission or after a simulated flight

Experimental Procedure

- Independent variable: system dynamics (varied by increasing aircraft roll time constant)
- Dependent variable: subjective measures of pilot opinion of task difficulty, usually the **Cooper-Harper scale** (CRefs. 7.705, 7.706, 7.707); inferred pilot lead (as used in the crossover model) (CRef. 9.511)
- Subject's task: fly a particular mission in an aircraft (sometimes with specific flight instructions), or control flight of a simulator for a specified period of time
- All subjects were experienced pilots

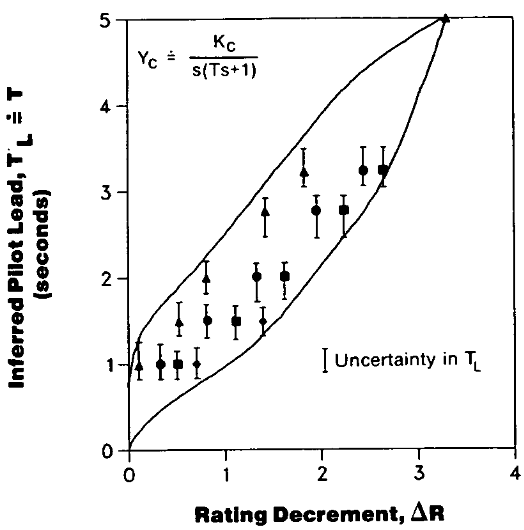

Figure 1. T_L (pilot lead time constant) versus pilot opinion rating. Increased rating decrements (i.e., increased values on the *x*-axis) correlate with decreased pilot ratings and increased pilot workload. (From Ref. 2, based on data of Ref. 1)

Experimental Results

- Pilot opinion of task decreases as lead time T_L increases, as seen in Fig. 1.

Variability

There is some variability involved in estimating T_L, which is indicated by the vertical bars in Fig. 1. Variability in Cooper-Harper ratings is not reported, but these generally correlate with other measures of task difficulty.

Repeatability/Comparison with Other Studies

Conclusions depicted in Fig. 1 are based on analysis of data from 12 studies.

Constraints

- Data are usually reported for average performance under typical operating conditions.
- Data reported are for roll motion only.
- There is some difficulty in connecting pilot ratings with specific aircraft parameters.
- Studies in aircraft were obviously limited to dynamics of that particular craft, with each type of aircraft yielding a range of parameters.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Ashkenas, I. L. (1965). *A study of conventional airplane handling qualities requirements: Part 1. Roll handling qualities* (AFFDL-TR-65-138). Wright-Patterson Air Force Base, OH: Air Force Flight Dynamics Laboratory. (DTIC No. AD627659)

2. McRuer, D. T., & Jex, H. R. (1967). A review of quasi-linear pilot models. *IEEE Transactions on Human Factors in Electronics, HFE-8*, 231-249.

3. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

Cross References

7.705 Cooper-Harper aircraft handling characteristics scale as a subjective measure of workload;

7.706 Cooper-Harper aircraft handling ratings as a function of secondary task instability;

7.707 Cooper-Harper scale modified for system workload assessment;

9.511 Modeling of the human operator: the crossover model;

9.518 Joint effects of first-order exponential lag and gain on target tracking performance;

9.519 Control order;

Handbook of perception and human performance, Ch. 39, Sect. 2.4

C-4

9.523 Varying Parameters of the Crossover Model

Table 1. Pilot equalization rules for various controlled elements.

Controlled Element Approximate Transfer Function in Crossover Region $Y(s)$	Pilot's Equalizer Form	Pilot's Describing Function $Y_p(j\omega)$	Location of Equalization Break Frequency
K_c	Lag- lead	$\frac{K_P e^{-j\omega\tau_e}}{T_I j\omega + 1}$	$\frac{1}{T_I} << \omega_c$
$\frac{K_c}{S}$	High-frequency lead	$K_P e^{-j\omega\tau_e}$	—
$\frac{K_c}{S^2}$	Low-frequency lead	$K_P(T_L j\omega + 1)e^{-j\omega\tau_e}$	$\frac{1}{T_L} << \omega_c$
$\frac{K_c}{S(TS + 1)}$	If $T > \tau_e$ use mid-frequency lead	$K_P(T_L j\omega + 1)e^{-j\omega\tau_e}$	$\frac{1}{T_L} \doteq \frac{1}{T}$
	If $T < \tau_e$ use high-frequency lead	$K_P e^{-j\omega\tau_e}$	—
$\frac{K_c}{(S/\omega_n)^2 + (2\zeta/\omega_n)S + 1}$	If low natural frequency ($\omega_n << 1/\tau_e$) use low-frequency lead	$K_P(T_L j\omega + 1)e^{-j\omega\tau_e}$	$\frac{1}{T_L} << \omega_c$
	If high natural frequency ($\omega_n > 1/\tau_e$) use lag-lead	$\frac{K_P e^{-j\omega\tau_e}}{(T_I j\omega + 1)}$	$\frac{1}{T_I} << \omega_c$

K_c = gain of the controlled element; K_P = pilot static gain; T_L = lead time constant; T_I = lag time constant; τ_e = effective time delay; s = Laplace operator; and $j\omega$ = frequency operator.

From D. T. McRuer & H. R. Jex, A review of quasi-linear pilot models. *IEEE Transactions on Human Factors in Electronics, HFE-8;* Copyright © 1967 IEEE. Reprinted with permission.

Key Terms

Bode plot; control order; crossover model; tracking

General Description

In the crossover model (CRef. 9.511), an operator first adapts to the system **transfer function** by applying some form of "equalization rule" (Table 1) to achieve system stability; the equalization values chosen for the lead and lag time constants (T_L and T_I, respectively) are those that yield a −20 dB/ decade slope for the magnitude ratio (of the Bode plot; CRef. 9.504) for a range of frequencies surrounding the crossover frequency (CRef. 9.511). The differences in pilot strategy and **describing function** for various system transfer functions are listed in Table 1.

After achieving stability, the operator then improves performance (according to the crossover model) by adjust-

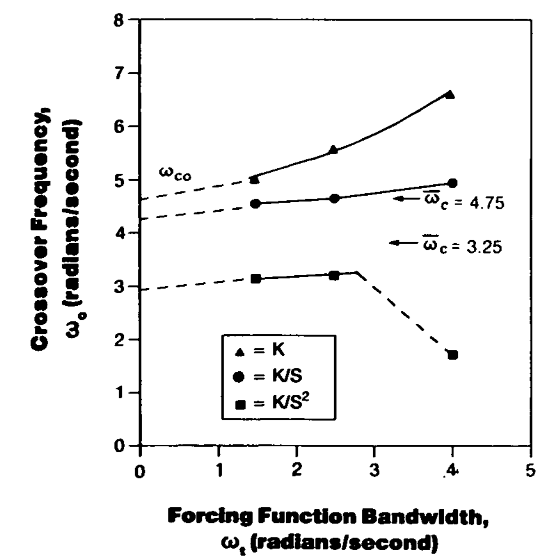

Figure 1. Crossover frequency as a function of input bandwidth for zero- (▲), first- (●), and second-order (■) systems. ω_{co} is the extrapolated value for the neutrally stable crossover frequency when input bandwidth equals zero. K is gain and S is the Laplace operator, a representation of a continuous signal that accounts for both frequency-domain and time-domain characteristics. (From D. T. McRuer & H. R. Jex, A review of quasi-linear pilot models, *IEEE Transactions on Human Factors in Electronics, HFE-8*. Copyright ©1967 IEEE. Reprinted with permission.)

ing the crossover frequency ω_c and the effective time delay τ_e. The crossover frequency is adjusted by changing operator gain so that the crossover frequency is always the same for any given system gain. Figure 1 shows that crossover frequency decreases as system order increases. However, crossover frequency is relatively unaffected by the forcing-function bandwidth except for very high bandwidths in second-order dynamics.

Decreasing the effective time delay increases the phase margin and thus also reduces system errors. Effective time delay τ_e increases with higher order dynamics, and decreases with increasing bandwidth (Fig. 2).

As the input bandwidth approaches (or exceeds) the crossover frequency, operators will reduce their gain and crossover frequency to keep control of the system (which would be impossible if they tried to track the higher frequencies). This strategy is called "crossover regression." The point for $\omega_c = 4$ for the second-order system in Fig. 1 is an example of crossover regression.

When conditions are favorable for tracking, relative error can be predicted by:

$$\bar{e}^2/\bar{i}^2 \doteq 1/3(\omega_i/\omega_c)^2$$

$\bar{e}^2$ is the mean of the squared errors; $\bar{i}^2$ is the mean of the squared input; ω_i is the input bandwidth; and ω_c is the crossover frequency. This equation is known as the "one third law" (Ref. 2).

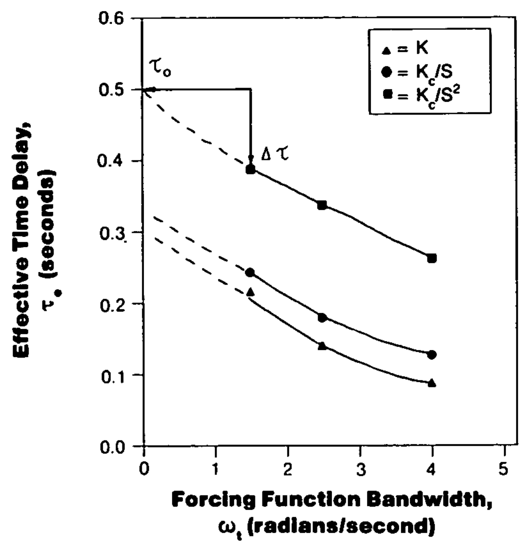

Figure 2. Effective time delay as a function of input bandwidth for zero- (▲), first- (●), and second-order (■) systems. τ_o is the basic time delay for a relaxed neuromuscular system. *K* and *S* have the same meaning as in Fig. 1. (From D. T. McRuer & H. R. Jex, A review of quasi-linear pilot models, *IEEE Transactions on Human Factors in Electronics, HFE-8*. Copyright © 1967 IEEE. Reprinted with permission.)

Applications

Any continuously controlled dynamic system, but especially aircraft control.

Methods

Test Conditions

- Series of related studies using a compensatory tracking task to investigate validity of crossover model of human tracking performance
- Oscilloscope mounted in front of subject with centered cross-hairs representing target
- Small cursor controlled by essentially frictionless control stick that could be spring-loaded
- Operator seated at comfortable distance from screen; controls could be easily reached
- Forcing functions generated by combining sine waves; spectral density varied over studies

Experimental Procedure

- Independent variables: forcing-function bandwidth, system dynamics (zero- to second-order)
- Dependent variable: crossover frequency or effective time delay, determined from plots of various characteristics of operator performance
- Subject's task: keep the cursor as close to the center of the oscilloscope as possible
- At least 2 or 3 pilots as subjects for each experimental condition

Experimental Results

- Bandwidth of forcing function generally does not affect crossover frequency, or gain, of the human operator (except for high frequencies in second-order dynamics).
- Increasing system order decreases crossover frequency.
- Increasing bandwidths produce shorter time delays in operator response.
- Increasing system order produces longer time delays.

Variability

The studies constitute an extensive series and corroborate each other's results.

Repeatability/Comparison with Other Studies

A number of studies and numerous applications have confirmed the repeatability of these results.

Constraints

- The models are limited to either fixed-base simulation or straight-and-level flight.
- The data are stable only for well-trained operators or pilots.
- The relationships hold best for single-axis displays; they change somewhat in dual-axis tracking.
- The "one-third law" holds for input bandwidths well below crossover frequency.
- Pilot equalization occurs most reliably in zero-, first-, and second-order systems; higher-order control imposes greater problems (CRef. 9.520)

Key References

*1. McRuer, D. T., & Jex, H. R. (1967). A review of quasi-linear pilot models. *IEEE Transactions on Human Factors in Electronics, HFE-8*, 231-249.

2. McRuer, D. T., & Krendel, E. S. (1957, October). *Dynamic Response of Human Operators* (ASD-TR-56-524). Wright-Patterson Air Force Base, OH: Aeronautical Systems Division. (DTIC No. AD110693)

Cross References

9.504 Bode plot representation of a gain element with pure time delay;

9.511 Modeling of the human operator: the crossover model;

9.520 Effects of system order and aiding on tracking performance

9.524 "Bang-Bang" Time-Optimal Tracking with Higher-Order Systems

Key Terms

Bang-Bang control; higher-order systems; optimal tracking; switching line; system control

General Description

Higher-order tracking systems (second-order and beyond) (CRef. 9.519) impose heavy task demands on operators; performance decreases as system order increases (even for well-trained operators).

One strategy used by human operators for higher-order systems is the double-impulse, or "bang-bang" control response, in which a control stick is moved rapidly from maximum deflection in one direction to maximum deflection in the opposite direction in a series of motions timed to rapidly bring the error to zero. To optimally control a system by means of the "bang-bang" strategy, control input must be switched from the positive to negative limit at precisely timed intervals along a "switching line" (Fig. 1) that represents the state of the system (a combination of its position and velocity) at each point in time. (There is a state of zero position error and zero velocity error when the switching line passes through the origin of the x and y axes.)

When the system is at point s, moving the control to the maximum in the opposite direction from the error would bring the system to point p; then maximally reversing the control would eliminate error and error velocity as quickly as possible. By using maximum movements, the operator does not have to integrate the amount of control that must be applied to obtain the required velocity; the integral and the switching time are directly proportional.

Operators can be trained to use the "bang-bang" strategy when appropriate; the distribution of second-order tracking amplitudes is distinctly bimodal rather than the Gaussian form that would be expected with continuous control. There is also a greater nonlinear remnant (CRef. 9.511), and direct evidence of pulsive behavior in the time domain control record.

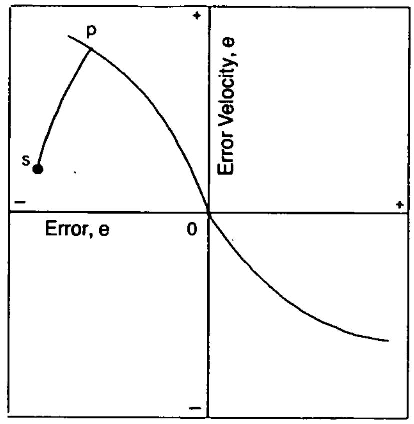

Figure 1. Representation of the state of a second-order tracking system showing the optimal timing (curved line) for error and error-velocity correction using a "bang-bang" correction strategy. s = a hypothetical state of the system for first application of maximum control; p = point of second maximal application. System will reach state of zero error and zero error velocity at origin of axes. (From *Handbook of perception and human performance*)

Applications

Spacecraft navigational systems; conventional tracking systems where error is likely to be increased by a transient.

Methods

Test Conditions

- Second-order tracking
- Phase plane trajectory of a system displayed with a switching line

Experimental Procedure

- Independent variables: various system trajectories and velocities
- Dependent variable: statistical distribution of operator's switching error (the difference between optimal switching time and operator's actual switching time)
- Subject's task: to throw a switch either to the left or right when switching line intersected system-state indicator (phase plane trajectory)
- 3 subjects, highly trained graduate students in mechanical engineering, with extensive training in use of the "bang-bang" strategy

Experimental Results

- Subject's responses closely approached an optimal switching strategy.
- "Bang-bang" control can be implemented only with a stick or switch control; rotary controls will be inappropriate under most conditions.

Repeatability/Comparison with Other Studies

- The "bang-bang" control strategy applies only to second-order and above systems.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. McRuer, D. T., Hofman, L. G., Jex, H. R., Moore, G. P., Phatak, A. V., Weir, D. H., & Wolkovitch, J. (1968). *New approaches to human-pilot/vehicle dynamic analysis* (AFFDL-TR-67-150). Wright-Patterson Air Force Base, Ohio: Air Force Flight Dynamics Laboratory. (DTIC No. AD667549)

*2. Miller, D. C. (1969). Human performance in time-optimal state regulation tasks. *Fifth Annual NASA-University Conference on Manual Control* (NASA-SP-215, pp. 483-522). Washington, DC: Aeronautics and Space Administration.

Cross References

9.511 Modeling of the human operator: the crossover model;

9.519 Control order;

Handbook of perception and human performance, Ch. 39, Sect. 2.5

9.525 Display Augmentation

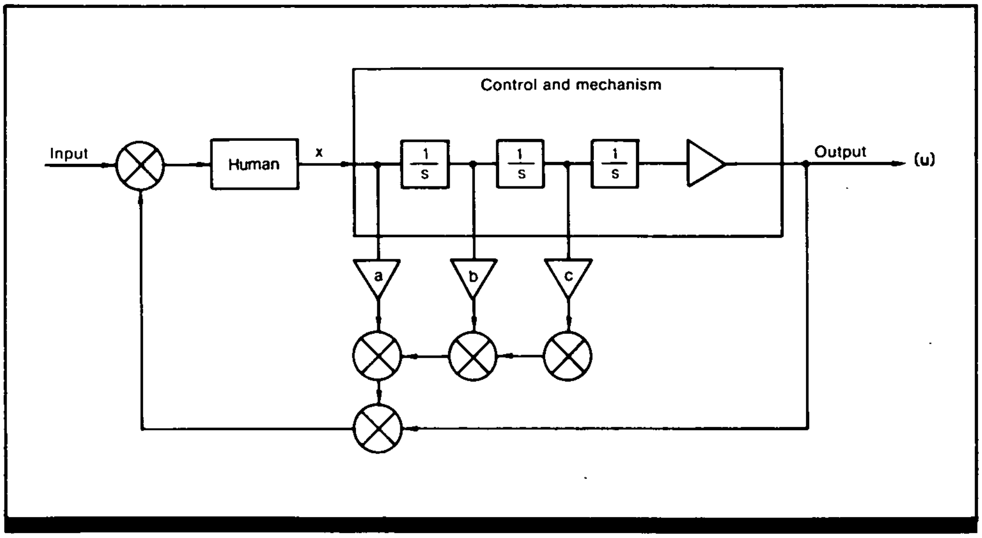

Figure 1. Display quickening of a third-order system. The inputs to each integrator are weighted and summed, with the inputs closer to the human operator weighted more heavily. (From *Handbook of perception and human performance*, adapted from Ref. 1)

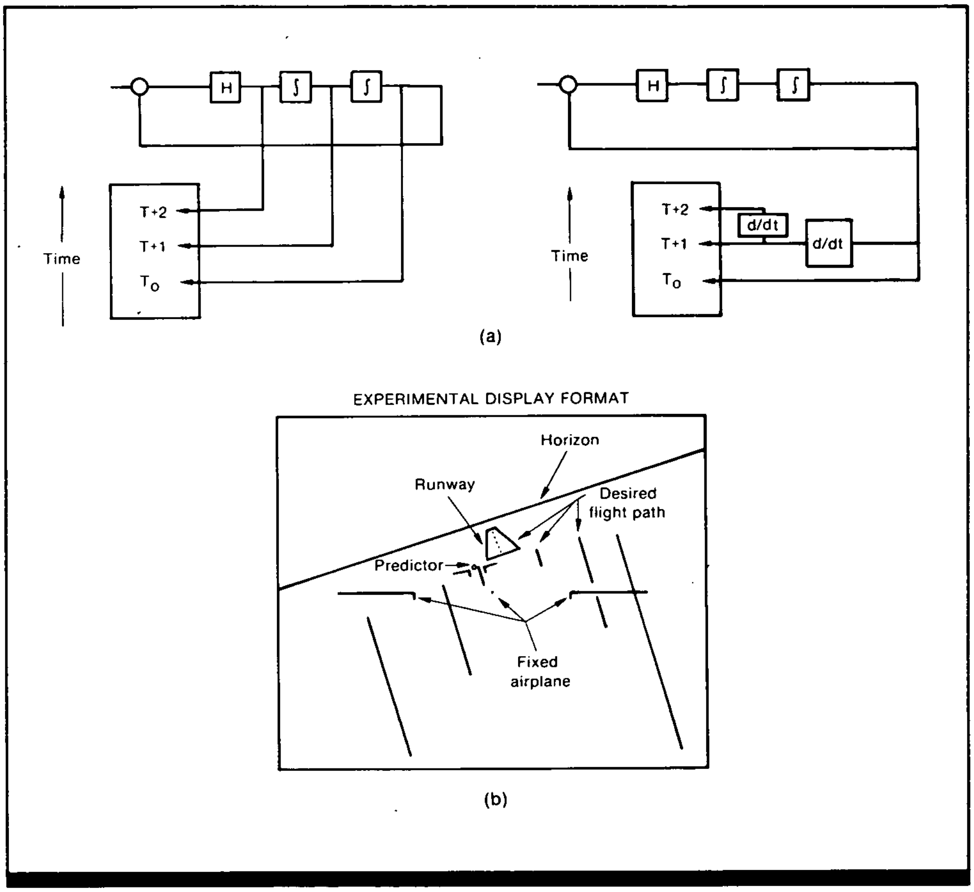

Figure 2. (a) Two methods of producing predictive displays for second-order systems; information may either be picked off before integration (left diagram) or first and second derivatives may be used (right diagram). (b) A typical predictor display (Ref. 2) showing a predicted future location of the aircraft. The oblique lines outline the desired flight path. (From Ref. 2)

Key Terms

Predictor instrument; pseudo-quickening; quickening

General Description

Providing information on error in the immediate future can help an operator control a dynamic system. The "look at the future" seems to allow an operator to reduce errors with less control effort. Providing information on future error is characteristic of four methods of display augmentation:

1) Display Quickening;
2) Predictor Display;
3) Phase Plane Display;
4) Pseudo-Quickening.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Display Quickening. This method of display augmentation consists of adding derivatives of the error (or system state) to the error. Figure 1 shows a block diagram of the method with weightings *a, b, c,* of the various derivatives. This has the advantage of allowing the operator to control error derivatives as well as the error. In addition, performance is improved because the system appears like a lower-order system to the operator. However, the operator is now tracking the display rather than the system, and cannot distinguish between error and error derivatives. Thus a nulled display could have a large error when that error is being rapidly reduced. This disadvantage could be critical in an accident or other emergency. Consequently, it may be desirable in some systems to provide a second indicator that shows true error (or system state). In aviation, flight-directors are examples of quickened displays.

Predictor Display. This method of display augmentation also adds derivatives to the error to provide a prediction of system state. However, the actual system state (or error) is also provided in this display method (Fig. 2b). Figure 2a shows two means of generating the display information. The first involves picking off system state components before they are integrated, and the second consists of computing the derivative of the output. A disadvantage of the predictor display is that the display may become cluttered by the additional information.

Both the predictor display and display quickening relieve the operator of the difficult task of calculating derivatives based on present position, and therefore improve performance. The performance increase is related to the accuracy of prediction possible. This accuracy depends on the disturbance bandwidth and the dominant time constant of the system. The future time span of reasonably accurate predictions is shown in Fig. 3 as a function of disturbance bandwidth and system **time constant**.

Phase Plane Display. This display method also gives an indication of future error by providing velocity information. An operator can use the phase plane display in an open-loop mode with **"bang-bang" control** motions (CRef. 9.524). While this produces better performance than an unaugmented display, it has a serious disadvantage in an environment with disturbance inputs. This is due to the fact that virtual motion on the display is a combination of true velocity and acceleration. The result is less than optimal performance when tracking a disturbance input.

Pseudo-Quickening. This method is a combination of quickening and the phase plane method. It consists of a conventional one-axis display with the addition of a discrete indicator to indicate when the hypothetical switching curve on the phase plane has been crossed (CRef. 9.524). By observing an intensification on the side of the cursor toward which control movement should be directed, the operator knows when to apply the bang-bang control reversal. In addition, a short anticipation of the switching line crossing can be programmed to accommodate the operator's time delay. This display method produces an increase in performance as effective as the phase plane, but also provides a positive transfer of training to the unaugmented case which the phase plane does not.

Applications

Augmented displays help an operator control any higher order system. This is particularly useful in flight vehicles for flight path control. It also applies to vehicles with long time constants (e.g., ships and submarines).

Key References

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2. Jensen, R. J. (1981). Prediction and quickening in prospective flight displays for curved landing and approaches. *Human Factors, 23,* 333-364.

3. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems.* Cambridge, MA: MIT Press.

Cross References

9.524 "Bang-bang" time-optimal tracking with higher-order systems;

Handbook of perception and human performance, Ch. 39, Sect. 2.5

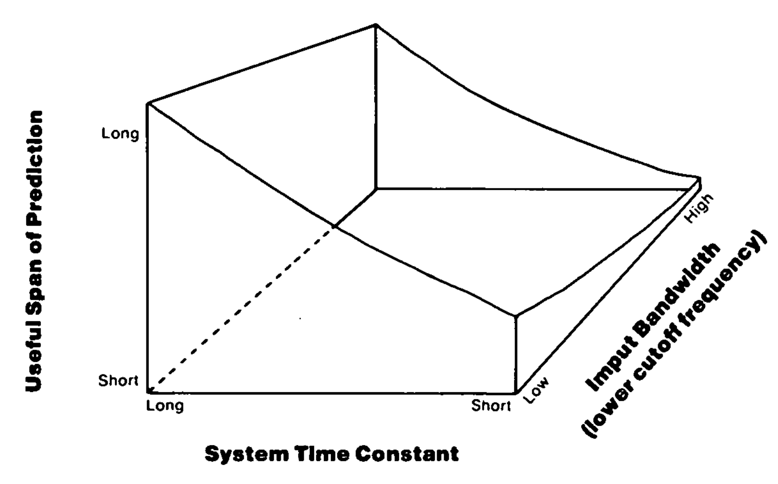

Figure 3. Qualitative relations among the time span for useful predictions, the system time constant, and the input bandwidth. (From *Handbook of perception and human performance*)

9.526 Augmentation of Control Dynamics

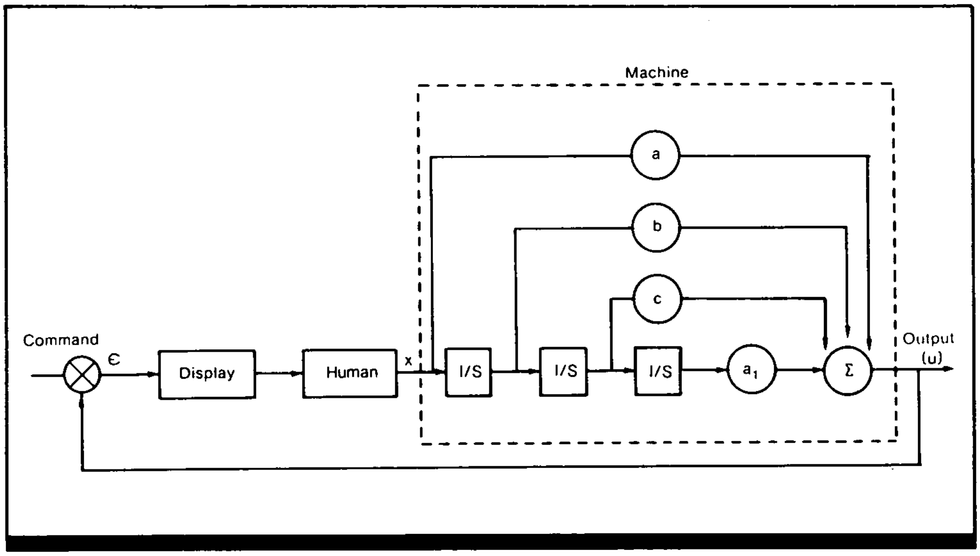

Figure 1. An aided third-order system in which the system transfer function has been changed by adding the weight inputs to the integrators into the control output. (From *Handbook of perception and human performance,* adapted from Ref. 1)

Key Terms

Augmentation; control aiding; control dynamics; higher-order systems; quickening; system dynamics

General Description

Three types of controllers can help an operator in controlling higher-order systems:

1) Control Aiding;
2) Matched Manipulator;
3) Discrete State Controller.

Control Aiding. This method of controller design consists of effectively changing system dynamics to a lower order by "picking off" the higher derivatives of a control signal and feeding them forward to the system output (with appropriate weighting factors). A **third-order system** with control aiding is shown in Fig. 1, where each feed-forward loop has the weighting factors *a, b,* and *c*.

Control aiding may be contrasted with display **quickening** (CRef. 9.525), in which the inputs to each integrator are "picked off" and fed back to the operator's display, thus providing information about performance sooner than if the system were left unquickened. Display quickening does not change the system transfer function, but merely changes the operator's display. Control aiding, on the other hand, affects the controls between the operator and the output, so that the system transfer function is actually changed. In the example in Fig. 1, the original transfer function, without aiding, was:

$$Y = K/S^3,$$

where *K* is gain and *S* is the Laplace operator for a third-order system. With aiding, the transfer function changes to:

$$Y = \frac{aS^3 + bS^2 + cS + 1}{S^3}$$

so that the higher-order components are weighted differently, effectively lowering the order of the system dynamics and making it easier to control. The choice of the weights can make the system simulate a combination of zero-, first-, or second-order control.

Aiding has been demonstrated to improve performance in many laboratory studies. It is difficult to apply, however, because of the physical properties of many systems. It is possible to alter the controls to some extent by the feed-forward circuitry of aiding, but substantial order reduction is impossible where the higher order is an intrinsic property of the physical system. Thus there has been greater interest in techniques that augment the operator's display, such as quickening or predictor instruments (CRef. 9.525), than in aiding.

Matched Manipulator. Another method of controller design is to select the controller force-position relationship in such a way that the controller position is an analog of the system output. Then the controller force is used as the system input. Thus the control position is proportional to the system output and the controller is "matched" to the system dynamics. This introduces useful kinesthetic cues, and produces better performance than conventional spring-loaded controls. A complete description of this method is given in Ref. 2.

Discrete State Controllers. Another method of improving control of higher-order systems is the use of "bang-bang" or discrete controllers. Because operators often control slugglish systems with this type of control motion switched at optimum times to nullify the error, it seems nat-

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

ural to provide only discrete state control. These controllers appear to work well in situations where the motions are predictable and there is little noise, such as in controlling spacecraft. However in noisy systems, this approach has not performed well. Reference 3 contains further information on this control augmentation method.

Applications

Control of systems where feed-forward loops can be introduced, such as nonvehicular systems.

Key References

*1. Birmingham, H. P., & Taylor, F. V. (1954). *A human engineering approach to the design of man-operated continuous control systems* (NRL-4333). Washington, DC: Naval Research Laboratories. (DTIC No. AD030879)

2. Herzog, J. H. (1968). Manual control using the matched manipulator control technique. *IEEE Transactions on Man-Machine Systems, MMS-9*, 56-60.

3. Young, L. R., & Meiry, J. L. (1965). Bang-bang aspects of manual control in higher-order system. *IEEE Transactions on Automatic Control, AC-6*, 336-340.

Cross References

9.524 "Bang-bang" time-optimal tracking with higher-order systems;

9.525 Display augmentation;

Handbook of perception and human performance, Ch. 39, Sect. 2.5

9.527 Inherently Unstable Dynamics: The Critical Tracking Task

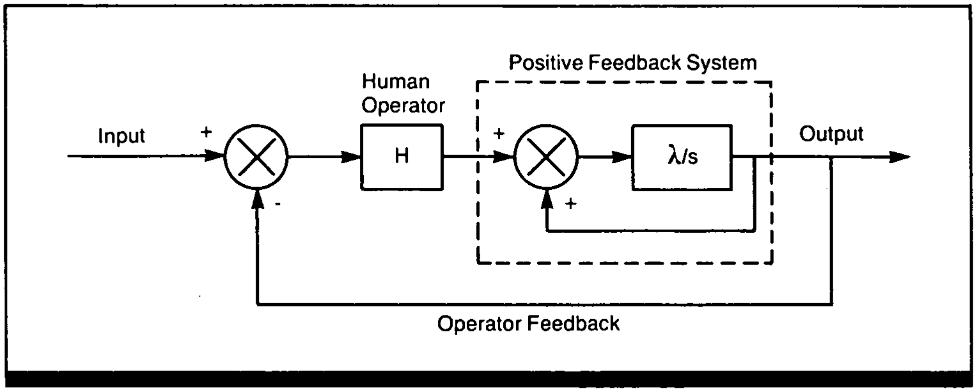

Figure 1. An unstable system with a positive feedback loop; the operator's output is integrated with gain λ and is added to system output, which creates the instability.

Key Terms

Controller task; Cooper-Harper rating; feedback; simulation; unstable dynamics; workload

General Description

Systems with positive feedback, such as that shown in Fig. 1, are inherently unstable. Without continuous compensatory control, the output is added to the input error, which increases the error and the system is unstable (CRef. 9.507). Such a system is like an "inverted pendulum," as in an attempt to balance a stick on the end of a finger. The system is in balance as long as the finger is exactly under the far end of the stick, but once the stick starts to fall, its rate of fall (analogous to system error) increases until it is no longer recoverable. The rate of increase, which is inversely proportional to the length of the stick, may be thought of as system gain, λ. The **transfer function** of such a system is $K/(T_jS - 1)$, where T_j is the system time constant, which is inversely proportional to system gain, λ.

The critical tracking task requires a human operator to provide continuous compensatory control to a positive feedback system (Fig. 1). The system gain is slowly increased until the operator loses control. The value of gain when control is lost is called the critical gain, λ_c. This process is illustrated in Fig. 2, where an operator is simultaneously controlling in both vertical and horizontal axes. Oscillations increase in amplitude and frequency until control is lost at the critical gain.

The limit in controllability is related to how fast an operator can respond. Operator response is limited by the human operator time delay, τ_e. Thus it seems reasonable that critical gain might be related to human operator time delay. Reference 2 reports that critical gain is highly correlated with both operator time delay and crossover frequency (CRef. 9.504), across different operators. The critical value of gain, λ_c, equals $1/(1.3\tau_e)$.

If a critical tracking task is cross-coupled with another tracking task (CRef. 9.511), then as subcritical values of λ are increased on one task, measured values of λ_c decrease on the other. Thus the system gain λ on the secondary task can serve as a measure of workload because it reflects the difficulty of the primary task:

$$WL = 1 - (\lambda_x/\lambda_c),$$

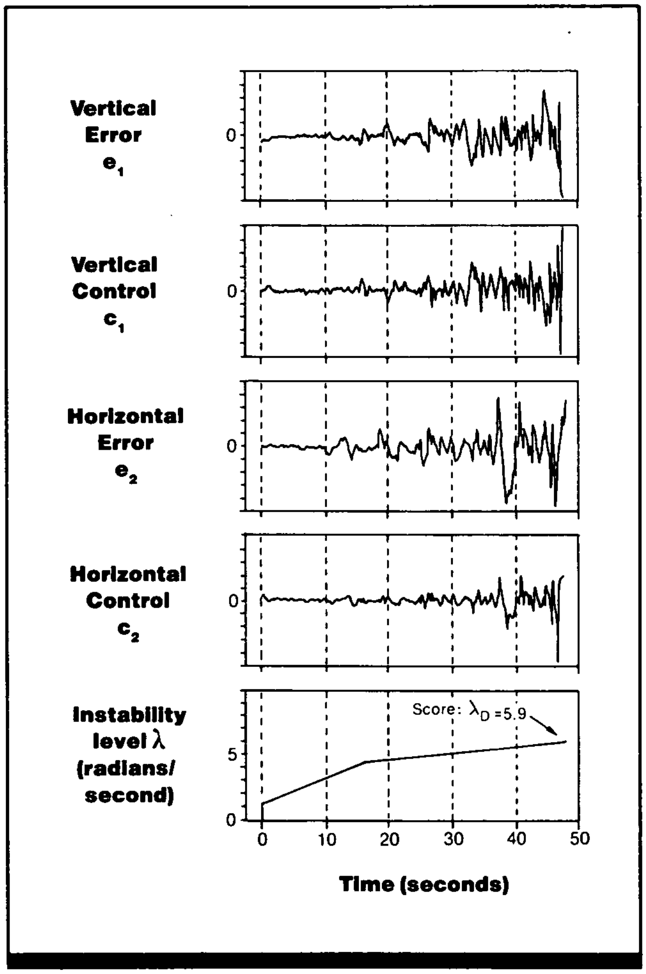

Figure 2. Control variables for a two-axis critical task as a function of time. (From *Handbook of perception and human performance*, after Ref. 2)

where λ_x is the subcritical value of λ on the cross-coupled task. This is illustrated in Fig. 3, where λ_x is slowly increased for the secondary task, Y_2, according to the error in the primary task, Y_1. This measure has shown excellent correlation with subjective ratings on the **Cooper-Harper scale**, a standard measure of pilot workload (Fig. 4).

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Applications

Simulations of manned booster rockets, helicopters, and very-short-take-off-and-landing (VSTOL) aircraft; measures of workload in cross-coupled tracking tasks.

Methods (Ref. 2)

Test Conditions

- CRT monitor with error bar that moves up and down ±5 cm in a **compensatory tracking** mode; error bar controlled by a stick moved up and down by thumb and fingers
- Input consisted of five combined sine waves of adjustable amplitude
- A controlled-element computer provided measures of a number of parameters, as well as control of the error bar and control of variations in gain, λ

Experimental Procedure

- Independent variable: **system order** (first-, second-, and third-order systems)
- Dependent variables: tracking-error variance relative to input variance, several describing functions (CRef. 9.511), **remnant** (CRef. 9.511), time delay (τ_e) from the critical instability task, **choice reaction time,** various psychophysiological measures (heart rate, breathing rate, neuromuscular activity, etc.)
- Subject's task: track the moving error bar as long as possible
- 4 subjects (3 pilots), trained to an asymptotic level on the task

Experimental Results

- In a positive feedback system (the critical tracking task), control becomes more difficult as system gain is increased until a critical value is reached; control then becomes impossible.
- The gain at which control is lost (λ_c) is highly correlated with human operator time delay (τ_e) and with crossover frequency (CRef. 9.511).
- The critical instability task described here can be used as an indicator of mental workload in tracking tasks; a cross-coupled task has been developed for this purpose.
- Some physiological measures of stress are correlated with tracking tasks for some individuals, but results are variable.

Variability

Results for task performance measures were reliable across subjects; results for psychophysiological measures were less so.

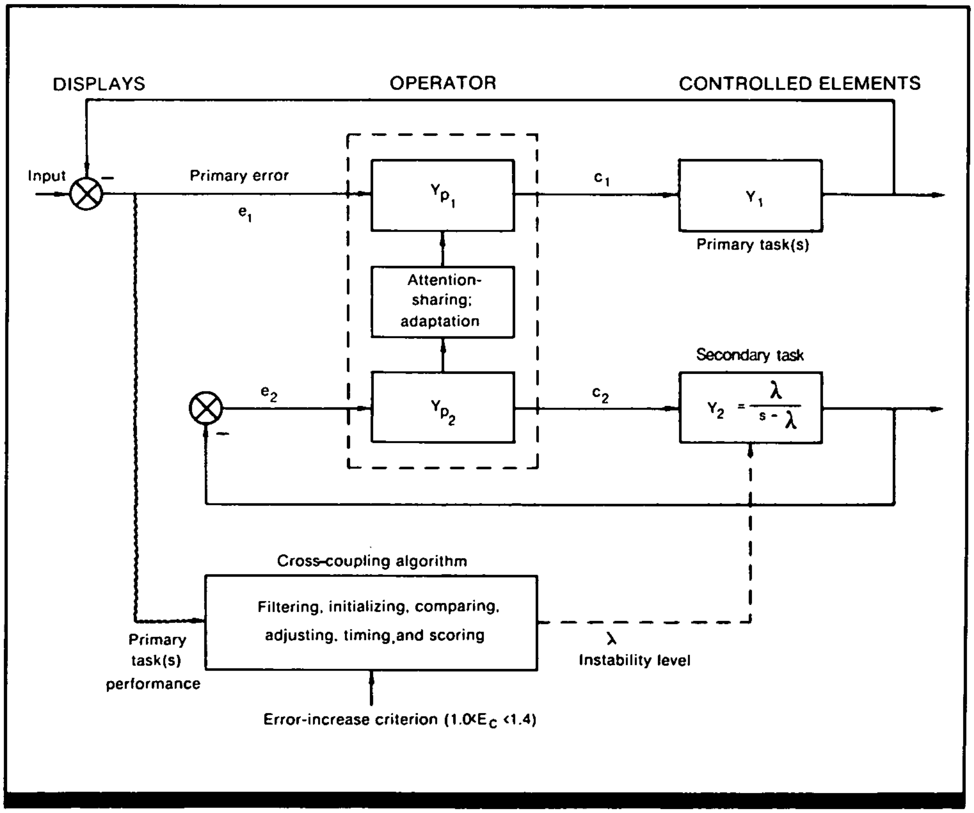

Figure 3. Cross-coupled critical instability task: e and c are error and operator control outputs, respectively, for the primary task (e_1 and c_1) and secondary task (e_2 and c_2). Changes in workload on the primary task are inversely reflected by changes in the instability element λ for the secondary task (i.e., the level of instability at which the operator can maintain control in the secondary task). (From Ref. 3)

Key References

1. Jex, H. R. (1979). A proposed set of standardised sub-critical tasks for tracking workload calibration. In N. Moray (Ed.), *Mental workload: Its theory and measurement* (pp. 179-188). New York: Plenum Press.

*2. Jex, H. R., & Allen, R. W.. (1970, April). Research on a new human dynamic response test battery, Part II: Test development and validation. *Sixth Annual Conference on Manual Control.* Wright-Patterson Air Force Base, OH: Air Force Institute of Technology.

3. Jex, H. R., & Clement, W. F. (1979). Defining and measuring perceptual-motor workload in manual control tasks. In N. Moray (Ed.), *Mental workload: Its theory and measurement* (pp. 125-178). New York: Plenum Press.

Cross References

9.504 Bode plot representation of a gain element with pure time delay;

9.507 Phase margin: a measure of stability;

9.511 Modeling of the human operator: the crossover model;

9.531 Multiaxis and multiloop control: manual control with multivariate systems;

Handbook of perception and human performance, Ch. 39, Sect. 2.6

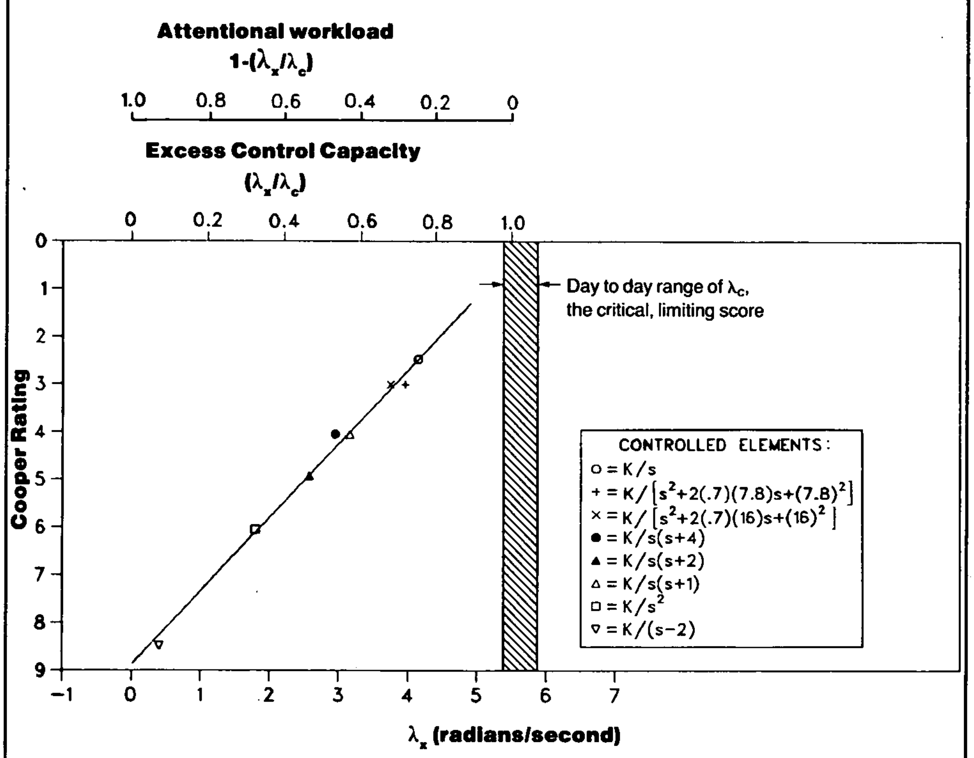

Figure 4. The correlation between pilot Cooper-Harper ratings of different handling qualities of various systems and the level of instability at which an operator can maintain control in a secondary task of a cross-coupled critical instability tracking task. λ_c is the maximum when there is no secondary task. (From Ref. 3)

Notes

9.528 Pursuit Versus Compensatory Displays

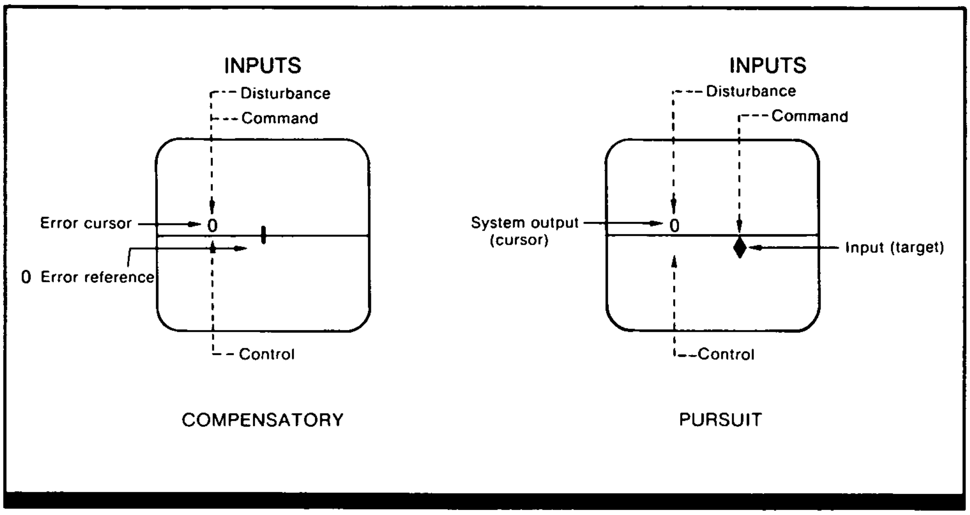

Figure 1. Single-axis displays for compensatory and pursuit tracking. (From *Handbook of perception and human performance*)

Key Terms

Compensatory displays; movement compatibility; phase droop; pursuit displays; simulation; tracking

General Description

The display for tracking a task may be either pursuit or compensatory. In a pursuit display, the **command input** cursor and the movement of the system output cursor are shown separately; the error is the distance between them. A pursuit display for a single-axis tracking task is shown in Fig. 1. With a pursuit display, system error can be traced to either a target course change or to the operator's control action.

In a compensatory display, only the error, which is the difference between the command input and the system output (resulting from both) control movements (and any **disturbance input**), is shown. This is illustrated in Fig. 1. With a compensatory display, the operator's task is to keep the error cursor as close to the error reference point as possible by moving a control stick in the direction opposite to the cursor movement, thus compensating for system error.

Generally, a pursuit display produces superior performance compared to a compensatory display. In pursuit tracking, the source of error is more easily identified and control stick movement is compatible with (in the same direction as) cursor movement.

External input to the operator-machine system may be either disturbance or command input. For example, wind gusts that occur while an aircraft is approaching a fixed runway are disturbance inputs. If the runway were on an aircraft carrier, command inputs would be controlling the movement of the carrier. The actions of the operator also affect the system. In a pursuit display, command input affects only the target, and disturbance and operator inputs affect only the cursor; consequently, the operator can perceive the sources of error separately; in contrast, in a compensatory display, all inputs affect the cursor and the sources of error cannot be separated. Thus, a pursuit display is generally superior and the advantage is greater where there is more than one source of input.

As the system goes from **zero**- to **first**- and higher-**order control**, the advantage of pursuit tracking remains, but is somewhat diminished. There is an interaction with input frequency, so that pursuit tracking is always superior in a zero-order system, but maintains superiority in higher-order systems only at high input bandwidths (CRef. 9.521). The superiority at high input bandwidths may be due to the absence of an increased phase lag (i.e., **phase droop**) which is normally observed in human responses to low-frequency inputs to higher-order systems. Phase droop is also present in compensatory tracking, but may be offset by a higher level of open-loop gain (the operator's response per unit input is greater) and a decrease in phase lag.

Applications

Choice of type of display for vehicle or process control (e.g., automated manufacturing, especially chemical or plant control); choice of display type where system dynamics and type of inputs are known, e.g., in a carrier landing situation; prediction of operator behavior where display type, system dynamics, and input are known, e.g., in a simulator; decisions on what aspects of a system to model in a simulator.

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Constraints

• To specify the degree of superiority of a pursuit display, system dynamics must be known or specified. The number, type, and frequency of course inputs must be known, i.e., the designer must know whether only command, only disturbance, or both inputs will be present, and the frequency of each. The combined frequency of all inputs is the effective frequency.

• Some studies that have shown equivalence between pursuit and compensatory tracking may have been subject to design flaws; thus the advantage of pursuit tracking may be maintained even with higher-order systems.

Key References

1. Chernikoff, R., & Taylor, F. V. (1957). Effects of course frequency and aided time constant on pursuit and compensatory tracking. *Journal of Experimental Psychology, 53*, 285-292.

2. Poulton, E. C. (1974). *Tracking skill and manual control*. London: Academic Press.

3. Sheridan, T. B., & Ferrell, W. R. (1974). *Man-machine systems*. Cambridge, MA: MIT Press.

Cross References

7.113 Probability of correctly operating continuous controls while monitoring dynamic displays;

7.114 Probability of correctly operating continuous controls while monitoring and tracking dynamic displays;

9.517 Temporal mismatch of motion and visual displays: effect on continuous tracking with simulated aircraft dynamics;

9.521 Effects of control aiding, input frequency, and display type on tracking of a random input;

9.529 Inside-out versus outside-in displays;

Handbook of perception and human performance, Ch. 39, Sect. 2.7

9.529 Inside-Out Versus Outside-In Displays

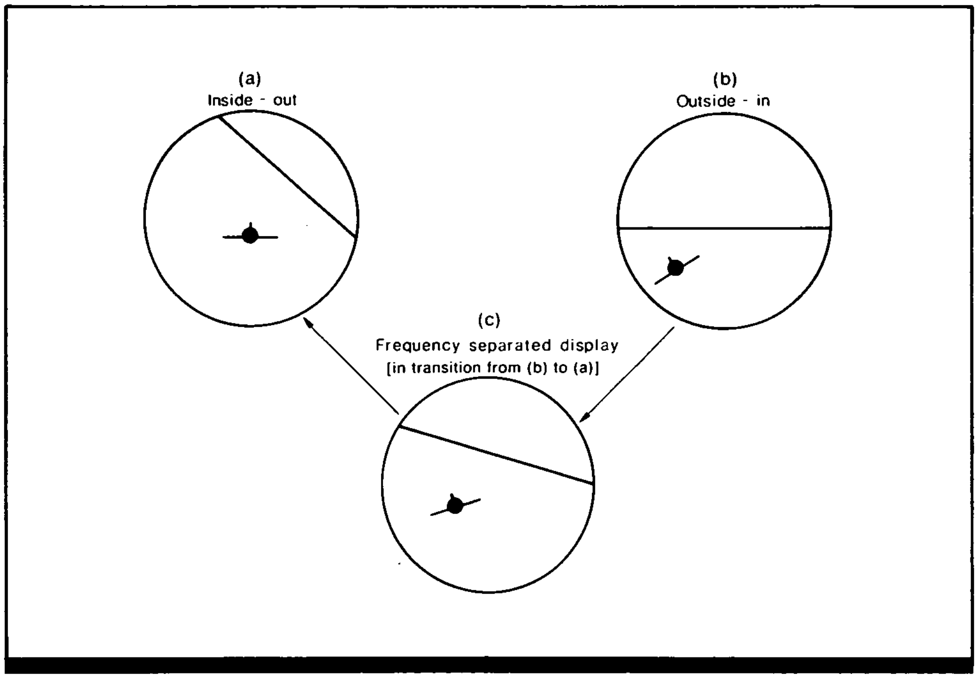

Figure 1. (a) Moving-horizon display (i.e., an inside-out display) with descending plane in a left bank; (b) fixed-horizon display (i.e., an outside-in display) providing same information as (a); (c) frequency-separated display in transition from (b) to (a), which occurs when attitude shown in (b) is held constant long enough for display rotation to occur. (From *Handbook of perception and human performance*)

Key Terms

Aircraft displays; frequency-separated display; heads-up display; horizon display; inside-out displays; movement compatibility; outside-in displays; simulation

General Description

A typical attitude display for an aircraft pilot shows a fixed representation of the plane and a moveable horizon that indicates pitch by vertical movement and bank angle by angular rotation; for example, the horizon indicator moves up as the plane noses down and turns clockwise as the plane banks to the left (Fig. 1a). This is called an inside-out display because it takes the viewpoint of the pilot looking out at the horizon from inside the plane. Thus, the inside-out display is compatible with what the pilot sees when looking out the aircraft window. This may be especially important with a **heads-up display** in which information is projected directly on the windscreen. Also, pilots are more experienced with the inside-out display.

For outside-in displays, the viewpoint is one of an outside observer who does not move in pitch, roll or yaw with the aircraft, but is fixed with respect to the earth Fig. (1b). The horizon indicator stays horizontal with aircraft roll, and the aircraft symbol tilts. With an outside-in reference, control movements are in the same direction as the motion of the displayed aircraft symbol; the control and display are compatible, usually resulting in better performance. The outside-in display is also compatible with the pilot's internal model of aircraft movement relative to a stable world.

Pilots are more experienced with the inside-out display and it is compatible with what is seen, while incompatible display-control motion must be contended with. The heads-up displays increasingly used in aircraft could be very confusing if they are of the outside-in type, since the directly viewed and heads-up-displayed views would be incompatible.

The advantages of both types of displays may be combined in a frequency-separated display, in which the display responds to the frequency of the pilot's control inputs; an inside-out display is produced during low-frequency inputs (e.g., steady flight) and an outside-in display is produced during high-frequency inputs from the pilot (e.g., during a change in heading). Thus the display mode is linked to the pilot's control motions.

Figure 1b represents a frequency-separated display (or outside-in display) immediately following a control bank to the left. Figure 1a represents the frequency-separated display after the attitude has been held constant long enough for the display to complete rotation, as shown in Fig. 1c. Figure 1a is also an inside-out display. Frequency-separated displays have been shown to produce superior performance in the laboratory and even more so in actual flight.

Applications

Design of displays for use in aircraft and in simulators; design of heads-up displays.

Constraints

• Application is limited to aircraft displays and *simulators* at present, because research has been limited to that context.

• Pilot experience, training, and individual differences may limit applicability.

• The pilot's mental model of the system, which affects the perception of what is compatible and what is not, cannot be assumed. More research is needed in this area.

Key References

1. Beringer, D. B., Williges, R. C., & Roscoe, S. N. (1975). The transition of experienced pilots to a frequency-separated aircraft attitude display. *Human Factors, 17*, 401-414.

2. Roscoe, S. N. (1980). *Aviation psychology*. Ames, IA: Iowa State University Press.

Cross References

9.528 Pursuit versus compensatory displays;

9.530 Characteristics of display formatting that influence tracking;

Handbook of perception and human performance, Ch. 39, Sect. 2.7

9.530 Characteristics of Display Formatting That Influence Tracking

Key Terms

Dwell time; intermittence-display; Korte's Law; previewing-display; tracking

General Description

A display may be only intermittently available to an operator, as when display updating is slow or resolution is low. This quantization of information is no longer harmful at a level determined by Korte's Law, which says that there is an optimal temporal viewing interval that depends on the spatial distance, so that shorter distances produce shorter optimal intervals.

To gauge the effects of intermittent viewing, we must specify the dwell time or viewing time (on-time), the frequency of intermittence, and the proportion of the viewing cycle that the display is visible. Varying one of these leads to changes in the others.

As shown in Fig. 1a, for a given off-time, tracking error decreases as viewing time increases, and intermittence has a greater negative effect on a more complex, less predictable, signal (three sine waves versus one sine wave). Figure 1b shows that tracking error decreases as frequency of intermittence increases (since this has the effect of increasing viewing time) until an asymptote is reached.

Previewing the command input by amounts up to approximately the duration of the operator's lag time for perceiving velocity or acceleration (CRefs. 9.516, 9.517, 9.518) also improves tracking performance. This is shown in Fig. 2, where error declines up to ~400 msec and then levels off.

Applications

Tracking tasks in which time-sharing with other tasks is important; displays with low resolution; displays which can be updated only intermittently.

Methods

Test Conditions

Study 1 (Ref. 1)

- Operator looks through transparent rotating wheel with opaque black sector
- Two white display markers move against a matte black background
- **Command input** (forcing function) for marker movement is either a 10-Hz single sine wave or three equal amplitude sine waves of 10, 7, and 5 Hz
- Error is 100 if operator does not respond at all (no operator input)

Study 2 (Ref. 2)

- Vertical **pursuit tracking task** with **first order dynamics** (CRef. 9.519) and random input with low-pass filter
- Display allowed 0-2-sec preview of input by displaying signal to be tracked as a portion of its own history; also allowed a short preview of 0-0.8 sec to appear as a tail on the right of the target symbol
- 51 cm (20 in.) average viewing distance

Experimental Procedure

Study 1

- Independent variables: duration of glimpses (dwell time or on-time), duration of blanks (off-time), complexity of command input
- Dependent variable: relative modulus mean error
- Observer's task: tracking task
- 12 young enlisted men as observers, with an unknown amount of practice

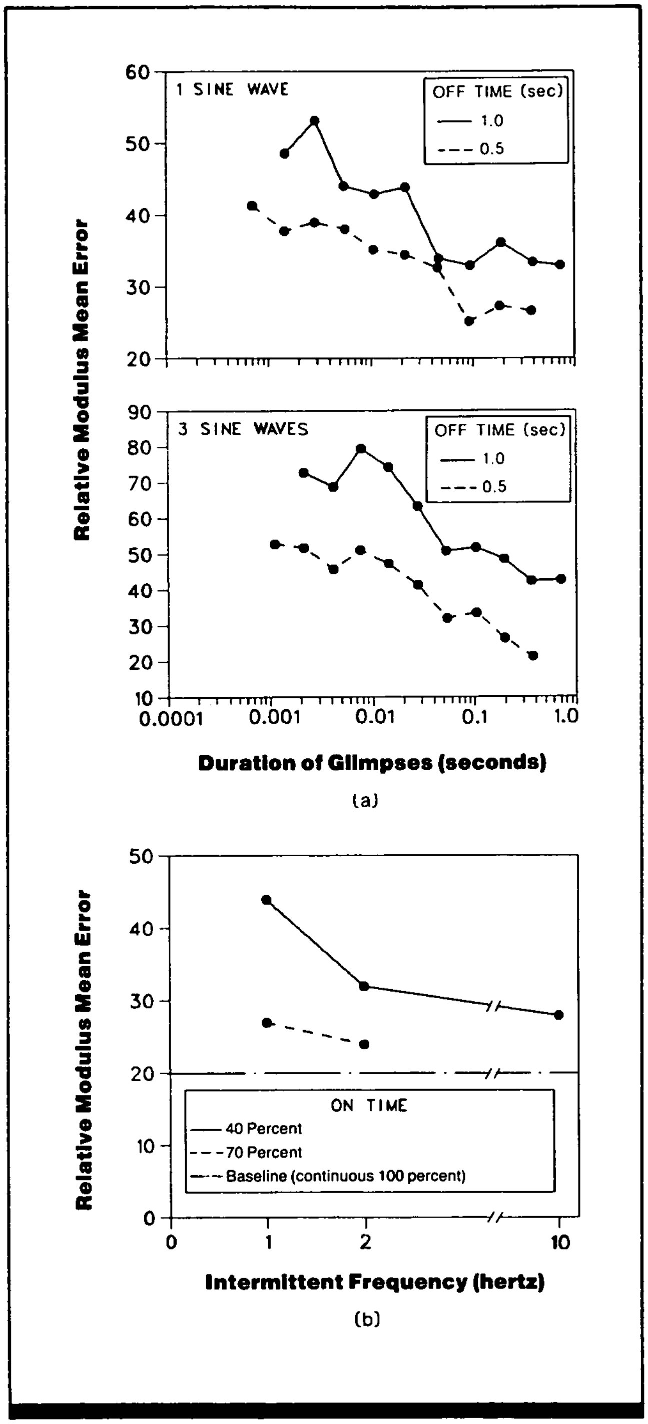

Figure 1. Tracking error as a function of (a) dwell time and (b) sampling frequency for intermittent display viewing (Study 1). For the two panels in (a), the one sine wave was 0.167 Hz and the three sine waves had a highest frequency of 0.167 Hz. The 10 Hz point in (b) is an interpolation of Poulton's results in Ref. 3. (From Ref. 1)

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Study 2
- Independent variable: preview time
- Dependent variable: a percentage form of tracking score, as illustrated in Fig. 2
- Observer's task: track the command input using a joystick
- 6 male graduate students as observers

Experimental Results

- Tracking performance improves (error decreases) for longer viewing time (increases in glimpse duration).
- Tracking error is higher for a longer off-time (1 sec as opposed to 0.5 sec).
- Tracking performance improves with higher frequency of intermittent presentation until ~2 Hz, and levels off thereafter. The increased viewing frequency makes up for shorter glimpses by increasing the total viewing time.

Variability

Study 1 reports reliable tracking error increases with variations in independent variables; standard deviations presented graphically in Study 2 are quite low, also indicating reliable results.

Repeatability/Comparison with Other Studies

A large number of studies have introduced intermittence in various ways (on the tracking or response marker or as a stepped marker) and have reported similar results.

Constraints

- The three parameters of on-time, off-time, and frequency of intermittence are interrelated; one cannot be varied without varying the other(s).
- With durations of presentation (glimpses) <100 msec, the brightness of the tracking marker is decreased in accordance with Bloch's law (brightness = duration × intensity), accounting for some of the poorer performance with intermittent displays.
- Frequency of intermittence did not overlap input bandwidth in these studies; this would probably produce even greater performance decrements.
- The intermittency reported here is regular; irregular intermittency, such as that occasioned by time-sharing another task, would also probably produce greater decrements.

Key References

*1. Poulton, E. C. (1974). *Tracking skill and manual control.* London: Academic Press.

*2. Reid, D., & Drewell, N. (1972). A pilot model for tracking with preview. *Proceedings of the 8th Annual Conference on Manual Control* (AFFDL-TR-72-92). (DTIC No. AD754908) Wright-Patterson AFB, Ohio: Air Force Flight Dynamics Laboratory.

3. Wickens, C. D. (1986). The effects of control dynamics on performance. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. II. Cognitive processes and performance.* New York: Wiley.

Cross References

9.516 Effect of transmission lag (pure time delay) in continuous tracking with zero-order dynamics;

9.517 Temporal mismatch of motion and visual displays: effect on continuous tracking with simulated aircraft dynamics;

9.518 Joint effects of first-order exponential lag and gain on target tracking performance;

9.519 Control order

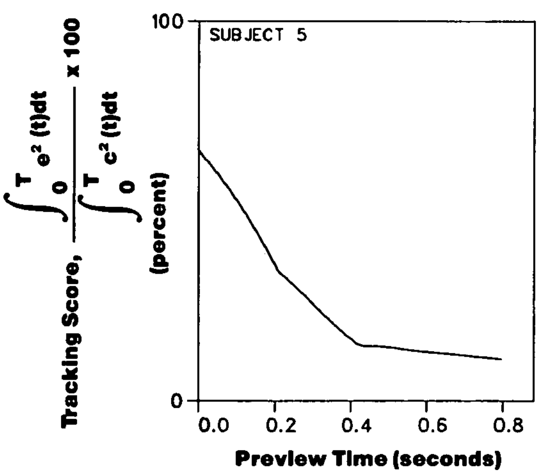

Figure 2. Improvement in tracking performance as a function of increasing preview time for a pursuit tracking task (Study 2). (Adapted from Ref. 2)

9.531 Multiaxis and Multiloop Control: Manual Control with Multivariate Systems

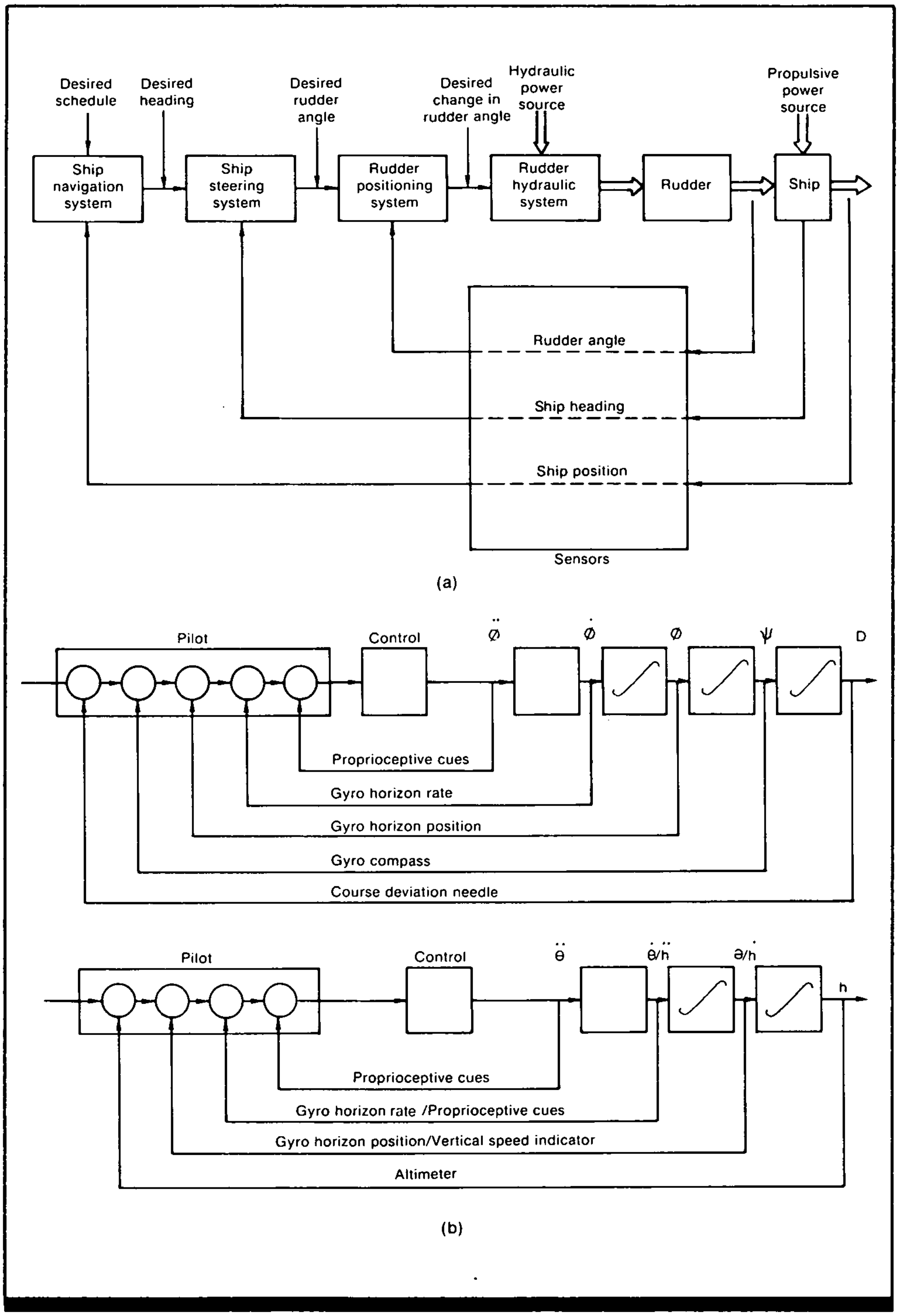

Figure 1. Hierarchically organized control loops for (a) steering control of a ship, and (b) lateral (top) and vertical (bottom) control of an aircraft. Integration is done from the inner loops to the outer loops (as indicated by symbols). [(a) from Ref. 1; (b) from Ref. 2)]

Key Terms

Control hierarchy; control loops; cross-coupling; multiaxis control; multiloop control

General Description

In most real-world tracking tasks, control is usually required in more than one axis; that is, multiaxis control is more common than single axis control. In addition, an axis may have several variables to be controlled; that is, multivariate control is common within each axis. Multiloop control is an ordered arrangement of these single-axis variables into appropriate feedback loops.

Control of any large system such as a ship, aircraft, or even a car involves control of a number of variables that can be arranged in a hierarchy of goals and subgoals (Fig. 1). For example, control of the heading of a ship involves the position of a hydraulic valve in the rudder control system (the inner loop in Fig. 1a) that results in a rate of movement of the rudder in the next loop out; in this next loop, the position of the rudder (rudder angle) results in an angular acceleration of the moving ship; finally, in the outermost loop, the angular position (heading) of the moving ship results in a rate of change of lateral ship position with respect to the desired course.

This progression from inner to outer loop, which is typical for moving vehicles (e.g., Fig. 1b for aircraft), involves going to larger, slower-changing elements and also from derivative to integral functions. Thus, to express it in a general form, the inner loop changes the *n*th derivative of the next outer loop, which changes the *m*th derivative of the third loop out, etc. The lowest-order variable is the inner loop variable and the highest order is the outer loop variable. The outer loop cannot be controlled except through the inner loop, but the inner loop may be controlled independently: controlling a ship's rudder without regard to the ship's heading is theoretically possible although it would obviously lead to dire consequences (which may not be the case in a process control situation).

Inner-loop processes are more easily automated than outer-loop processes and automation should proceed from the "inside out." The automation would thus allow an increasing range of freedom in the outer loops of the hierarchy.

An important aspect of multiaxis control is the cross-coupled task, a tracking task in which the control of one axis may influence the behavior of another. For example, the roll and pitch of an aircraft are under essentially different control systems, but rolling the aircraft generally results in a downward pitch that entails compensatory control movement. Cross-coupling may be very high (the variables are highly correlated) or very low (the axes are almost independent).

If two or more axes are not cross-coupled (i.e., they are completely independent), the operator must perform a dual-axis, independent tracking task. For example, separate remotely controlled vehicles or a remote manipulator with two independently controlled "hands" require dual-axis independent tracking.

Applications

Control of moving vehicles; process control; remote control of vehicles or robots; remote control of manipulators.

Key References

1. Kelley, C. R. (1968). *Manual and automatic control* (pp. 27-34). New York: Wiley.

2. Roscoe, S. N. (1980). *Aviation psychology* (pp. 33-38). Ames, IA: Iowa State University Press.

Cross References

9.533 Multiaxis separated displays;

Handbook of perception and human performance, Ch. 39, Sect. 2.8

9.532 Displays of Derivative Information

Table 1. Examples of presentation of derivative information about system motion.

Visual Presentation Characteristic	Examples	Effect on Performance	Source
Velocity displayed as position	Speedometer; vector flowing from target with length proportional to velocity	Superior performance	Refs. 6, 7
"Positionless" velocity indicator	Rate of wheel turn; rate of movement of moire pattern	Not as good as position matching	Ref. 7
Velocity displayed on cursor	Vector proportional to velocity flows from cursor	Tracking error reduced considerably	Ref. 6
Peripheral display of velocity	"Barber pole" or streaming; flash rate of flashing light	Tracking error reduced	Refs. 1, 2
Redundant display	Peripheral display in addition to critical display element	Assists performance in third-order and above systems	Refs. 5, 8

Key Terms

Acceleration; higher-order systems; kinesthetic cues; peripheral display; simulation; velocity information; vestibular cues

General Description

Frequently, in tracking tasks, only one element (cursor) is displayed, and all other information necessary to perform the task must be derived from it. Particularly in higher-order systems, where exponential lag generally makes it necessary to generate lead in performance (CRef. 9.523), velocity, or derivative, information must be obtained by the operator. It is possible for the human operator to use position and velocity information separately; for example, using separate controls for position and velocity for one display cursor can aid performance (Ref. 4). Thus information about higher-order derivatives, such as velocity and acceleration, from any source, is important for operator control of a system. Derivative information may be presented in a number of ways and may be explicitly presented as position, which is especially helpful. Several types of displays are outlined in Table 1 with examples, effects, and sources.

Information about velocity and acceleration (derivative information) can also be sensed through vestibular or head position cues from the middle ear and kinesthetic or "seat of the pants" cues that rely on the pressure of motion exerted on the body by a moving vehicle. The effects of vestibular cues are summarized in Table 2.

Applications

Design of displays for vehicle motion and control, particularly vehicle motion with strong higher-order components in their equations of motion.

Constraints

- The direction of motion of any auxiliary display, such as a peripheral display, must be made compatible with operator expectancies if it is to aid and not hinder performance.
- Vestibular and kinesthetic cues can be very misleading in a moving base simulator, as well as in an actual vehicle, if they are inconsistent with visual cues. (see Table 2).
- The use of vestibular and kinesthetic cues in a simulator is critically dependent on cue accuracy, particularly with regard to time lags.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

9.523 Varying parameters of the crossover model

Table 2. Examples of key motion effects in the pilot-vehicle system. (From Ref. 3)

Situation	Vestibular Sensors Primarily Involved: Utricle	Vestibular Sensors Primarily Involved: Semicircular Canals	Comments
Attitude control in straight and level flight		X	Semicircular canals can aid total pilot equalization by providing a higher order lead
Steady turn	X	X	Illusion of straight and level flight; G_{sc} and G_u terms are washed out
Straight and level after steady turn		X	Sensation opposite of turning: visual sensation of tilt; G_{sc} and G_u are dominant in creating these sensations
Steady acceleration in horizontal flight, pushover from steady climb	X		Sensation of nose-up change in attitude
Deceleration	X		Sensation of pitch-down change in attitude
Straight and level after high angular path (>60 deg/sec aerobatics)		X	Sensation of turning
Straight flight after long-time high-rate rolls		X	Nystagmus, blurred vision, reversal of background
High-frequency pitching rotations, etc.		X	Blurred vision

9.533 Multiaxis Separated Displays

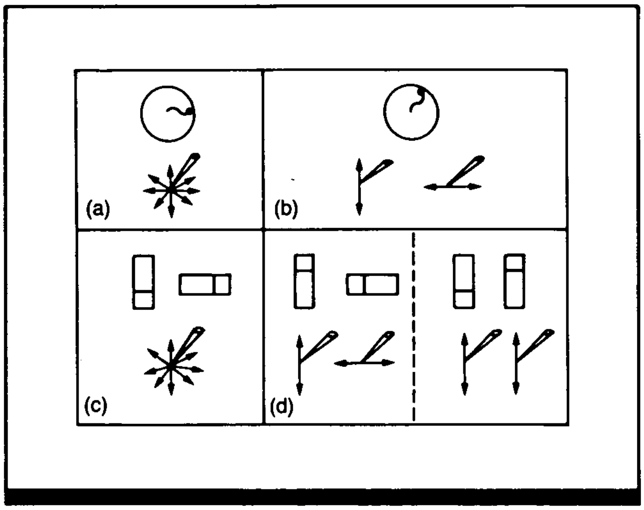

Figure 1. Separation or integration of multiaxis displays and controls. (From Ref. 2)

Key Terms

Control; multiaxis displays; tracking

General Description

Operators must often track more than one input simultaneously. Perhaps the most salient example of this is in the control of vehicles that move in 6 deg of freedom, such as a helicopter or spacecraft; a less extreme example is the control of pitch and roll in a conventional aircraft. Such multiaxis control exacts a cost in terms of performance, but the cost is greatly influenced by the physical configuration of the controls and displays combined with the nature of the task controlled in each axis.

In particular, displays and controls may be separated or integrated (Fig. 1). Complete integration of both is shown in Fig. 1a, where one display element (usually a cursor) is controlled by one movement of a control element, such as a joystick. The controls can be separated, so each axis of a single cursor is controlled by a different stick (Fig. 1b) or the display can be separated so that each axis is displayed separately but controlled by a single stick (Fig. 1c). Finally, both displays and control can be separated (Fig. 1d); other configurations are possible, although the right-angle placement as shown is generally superior.

In designing display and control systems for multiaxis tracking, three questions should be addressed.

1. What should be the display-control configuration, i.e., should displays and controls be integrated or separated?

2. If displays are to be separated, what should be their relative position? If integrated, how should their attributes be combined?

3. How should display axes relate to control axes?

From the point of view of human performance, these are complex questions and design decisions should be based on the data collected from a number of studies (CRefs. 9.534, 9.535, 9.536, 9.537).

Key References

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Cross References

9.534 Multiaxis separated displays: parafoveal tracking;

9.535 Multiaxis separated displays: scan patterns;

9.536 Multiaxis effects of control order;

9.537 Multiaxis effects: extensions to more than two axes

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

9.534 Multiaxis Separated Displays: Parafoveal Tracking

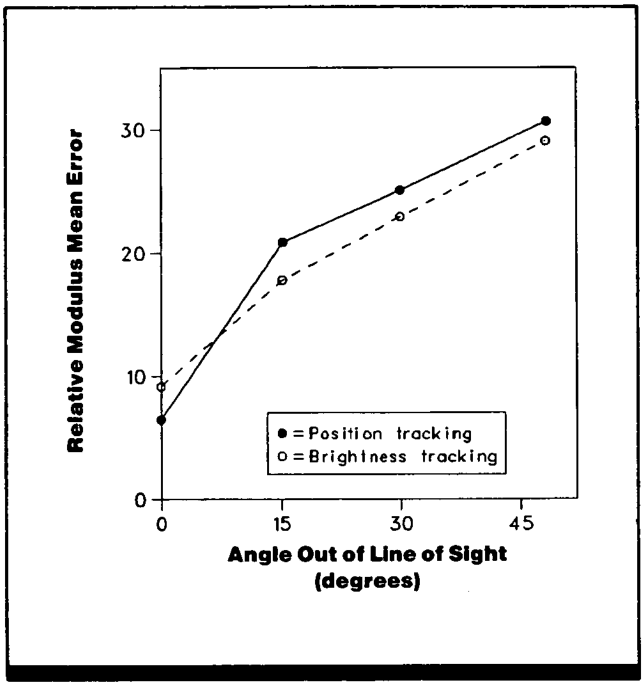

Figure 1. Tracking error as a function of distance from fovea (Study 1). (From Ref. 2)

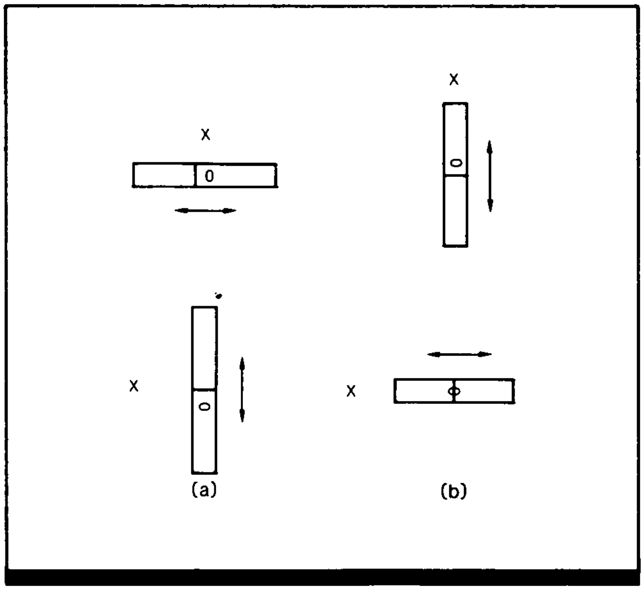

Figure 2. Preferred orientation of single-axis parafoveal display as a function of fixation point X (Study 2). Relative positions of fixation point X and displays do not provide a zero-reference axis to aid in tracking. (From *Handbook of perception and human performance*)

Key Terms

Foveal vision; line-of-sight; multiaxis displays; peripheral tracking; tracking

General Description

When two or more displays at separate locations must be tracked at the same time, performance declines in both tasks. It is still possible, however, to track a moving target in peripheral vision, i.e., from the "corner of the eye." This is shown in Fig. 1, where error increases as distance from the **fovea** (direct line of sight) increases. Figure 2a shows a preferred configuration for display orientation when the display must be tracked while fixating on X. The configuration in Fig. 2b yields poorer performance because the point of fixation X cannot be associated with any point on either the vertical or horizontal display to establish a zero-reference axis for movement.

Applications

Tracking of more than one input at the same time, as is commonly done in aircraft control.

Methods

Methodological details are given in Table 1.

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Experimental Results

Study 1

- Performance declines markedly with increasing distance from the fovea.
- Position tracking is slightly better than brightness tracking at the fovea, but the reverse is true for parafoveal tracking.

Study 2

- Error increases as the display moves from foveal to peripheral vision.
- The increase is threefold when extrapolation is possible, and eightfold when it is not.
- Error is approximately twice as great when tracked target is above the fixation point than when it is below it.
- Error is approximately 50% greater when tracked target is to the right of the fixation point as when it is to the left.

Repeatability/Comparison with Other Studies

The two studies support each other and are supported by several more recent studies.

Constraints

- Only zero- and **first-order dynamics** were studied. The magnitude of the effect may be different under higher-order dynamics.
- Only display effects are reported here. There are also some problems with motor performance when a multiaxis control is manipulated by one hand.
- Subjects were allowed to glance at displays in Ref. 2.

Key References

*1. Levison, W. H., Elkind, J. I., & Ward, J. L. (1971). *Studies of multi-variable manual control systems: A model for task interference* (NASA CR-1746). Washington, DC: National Aeronautics and Space Administration.

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Cross References

9.533 Multiaxis separated displays;

Handbook of perception and human performance, Ch. 39, Sect. 2.8

Table 1. Details of experimental methodology.

Test Conditions	Experimental Procedure
Study 1 (Ref. 2)	
Pursuit task with zero-order dynamics (position control)	Independent variables: degrees out of line of sight, type of tracking (target position or target brightness)
Input was a pure sine wave of 0.20 Hz	Dependent variable: amount of integrated absolute error
Target movement amplitude was 3 in. for position tracking, 0-17.1 cd/m^2 for brightness tracking	Subject's task: track a target while fixating a point
Fixation points were 0, 15, 20 or 45 deg from fovea	6 subjects with extensive practice
Study 2 (Ref. 1)	
Subjects tracked various arrangements of the four-axis display configuration shown in Fig. 2	Independent variables: configuration of tracking task, degrees out of line of sight
Each display component consisted of a moving error bar and a stationary reference line presented on an oscilloscope	Dependent variable: root-mean-square error
Subject fixated and tracked either foveally or 16 deg or 22 deg peripherally in the four configurations shown in Fig. 2. In Fig 2a, it is possible to extrapolate a reference point from X to the display motion because display motion is orthogonal to a zero-reference axis that can be axis established. In Fig. 2b, extrapolation is not possible because X cannot be used to establish a zero-reference axis.	Subject's task: track a target while fixating a point
A single display was fixated during each trial and two (or more) axes were controlled simultaneously by two, two-axis manipulators, one for each hand, to provide display-control compatibility	4 subjects, instrument-rated aircraft pilots
Input was velocity (first-order) controlled and constructed from a number of sinusoidal components	

9.535 Multiaxis Separated Displays: Scan Patterns

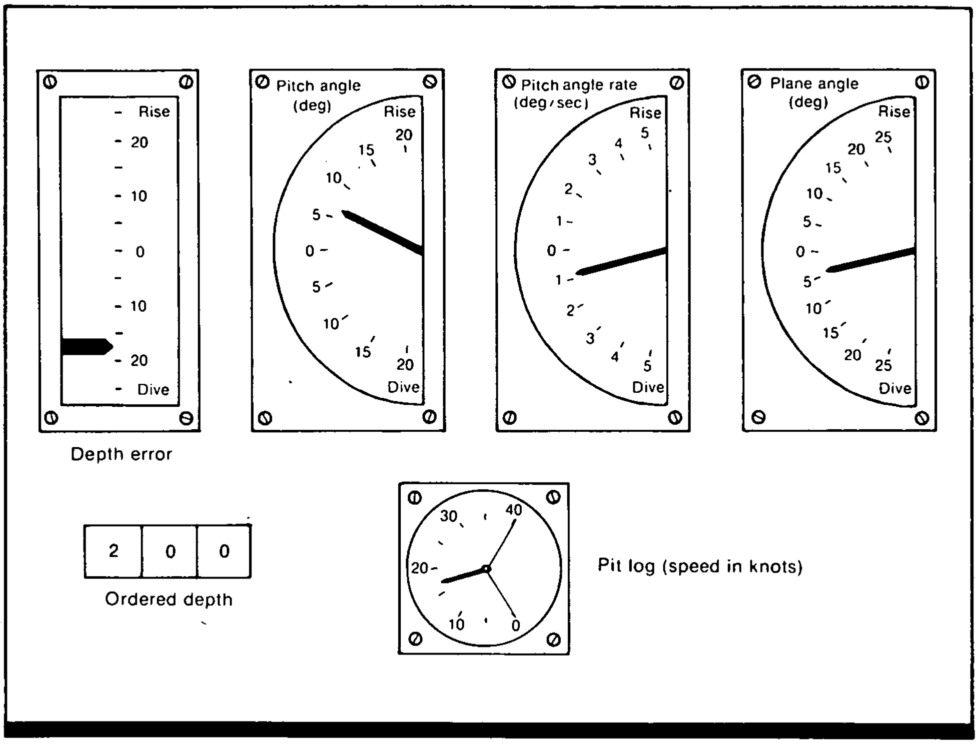

Figure 1. Submarine depth-control displays in an optimal configuration that agrees with the operator's model of the system. More rapidly changing displays are on right, which is the preferred side for eye fixation. (From Ref. 1)

Key Terms

Attention cueing; display configuration; eye movements; multiaxis displays; scan patterns; target acquisition; visual fixation; visual tracking

General Description

Operators move their eyes in a regular pattern across the instruments in a display. This is called a scan pattern, which can be tracked and recorded with various types of devices. The scan pattern varies with what is displayed and with the skill level of the operator, and it systematically reflects operator information needs. The most frequently fixated instrument during flight is the attitude indicator, which presents the lowest order of information in the flight control loop (consequently, the tracking of attitude requires the least amount of lead time because attention is most likely to be focused on it).

The most frequently fixated displays should be located in the center of the field of vision, and instruments viewed together should be located near one another; with functional grouping, the total distance traveled in fixation transitions will be minimal. Once the scan pattern is known (from investigations with an eye movement camera), the instruments can be arranged in this way. One overriding exception could be an emergency display, which should be centrally located even if it is rarely fixated during non-emergency conditions.

Two other principles may influence decisions about display placement. First, displays may be placed in order of increasing derivatives; for example, the submarine depth-control displays to the left in Fig. 1 are for slower changing, higher order, "outer loop" (CRef. 9.531) variables. This is consistent with an operator's internal model of how the system works (Ref. 1). In a set of displays of this type, zero indications should all be located in an equivalent place and the range of scale movements should be roughly similar.

The second principle (Ref. 2) is that operators prefer to fixate the upper right quadrant. In an investigation involving tracking four elements, one in each quadrant, the percentage of fixation time for each quadrant is 47% for upper right, 20% for upper left, 20% for lower right, and 13% for lower left. This results in roughly equivalent root-mean-square error (CRef. 9.510) on all four axes, and seems to be related to the upper right quadrant benefiting more from foveal (central) vision and losing more in parafoveal vision. Consequently, those displays (e.g., print) that require the acuity of foveal vision (i.e., the best vision for fine detail) should be placed toward the upper right when possible.

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Applications

When several displays need to be arranged on a panel for the control of a vehicle or process, scan patterns and the other principles may be used to guide the location of the displays relative to one another in the operator's field of vision.

Empirical Validation

Scan patterns have been extensively investigated with eye movement tracking devices in innumerable studies in laboratory and aircraft settings, and have always been shown to reflect an operator's information needs.

The principle of ordering according to control order is largely theoretical and has received little empirical validation. The viewing time in upper right quadrant is a frequent observation in studies of foveal and peripheral vision and the implications for performance have been confirmed (Ref. 5).

Constraints

- Scan patterns cannot be inferred from judgments about the importance of instruments in a display; they must be empirically validated using an eye movement camera or similar device for tracking eye movements.
- Scan patterns do not always give a clear indication of how a display should be arranged, i.e., several portions of a display may be fixated for nearly equal amounts of time. Then, other criteria like the ones given must be used for display arrangement.
- The principle of ordering according to control order obviously does not apply in situations where all dynamics are the same, as might occur in process control.

Key References

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Cross References

7.311 Application of optimal control theory to monitoring performance;

7.501 Factors affecting visual search with monochrome displays;

9.510 Error, system control criteria, and human limitations in error control;

9.530 Characteristics of display formatting that influence tracking;

9.531 Multiaxis and multiloop control: manual control with multivariate systems

9.536 Multiaxis Effects of Control Order

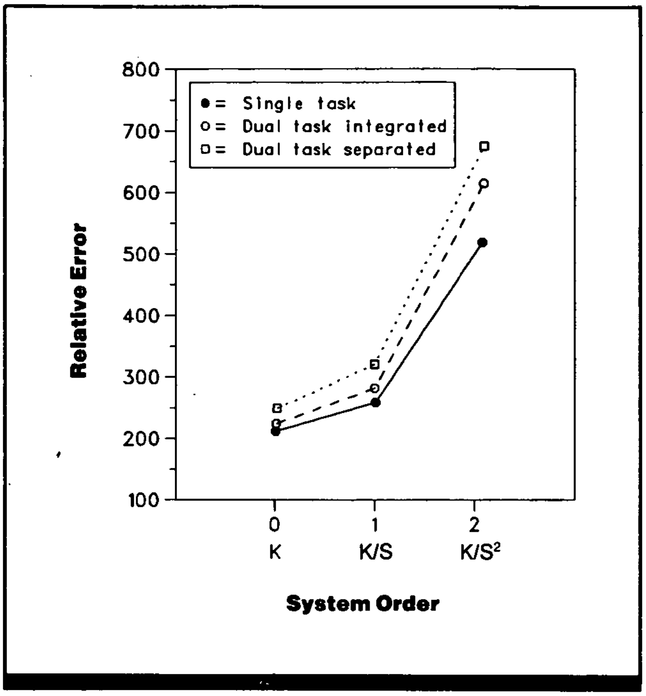

Figure 1. Single- and dual-axis tracking as a function of control order. K is gain (position of the cursor) and S is the Laplace operator, a representation of a continuous signal that accounts for both frequency-domain and time-domain characteristics. (From *Handbook of perception and human performance*, based on data from Ref. 1)

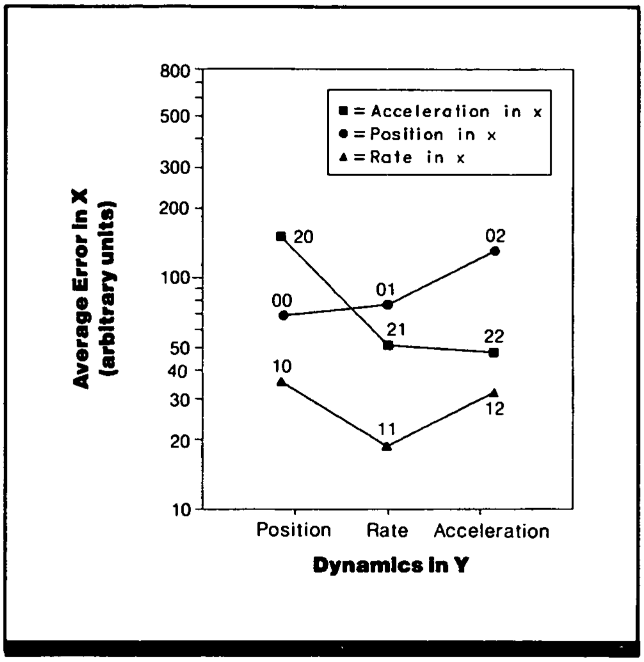

Figure 2. Tracking with same and different dynamics in each dimension. For each point, the first digit is control order for measured task and second digit is control order for paired task. (From Ref. 2)

Key Terms

Dual-axis tracking; higher order dynamics; multiaxis control; system dynamics; tracking

General Description

Tracking tasks may be performed in one dimension (one cursor moving in one axis) or in two dimensions (two axes, one or two cursors). In two-dimensional tracking, one cursor may move in two dimensions (integrated display) or a separate cursor may be used for each dimension (separated display). In the latter case, only one control may be used (integrated control) or each cursor may be controlled separately (separated controls). It is also usually true that a vehicle such as a helicopter or spacecraft, which can maneuver horizontally and vertically, has a different set of dynamics in each dimension.

Multiaxis tracking tasks yield poorer performance than single-axis tasks; further difficulties are imposed by higher-order dynamics and by having different dynamics in each dimension. Display and control integration or separation interact with each of these factors in regular ways, as noted in the Experimental Results section.

Applications

Design of vehicle or process control when controlled element moves in two dimensions, especially when dynamics are different in each dimension as in helicopter or spacecraft control.

Methods

Test Conditions

- Compensatory displays used in all three studies
- Input forcing functions were either random (Fig. 1) or sine wave (Figs. 2, 3)
- Dynamics went from position (K) to acceleration (K/S^2) control
- Single- and dual-axis controls and displays were tracked in each study: single- versus dual-axis display and control, integrated versus separated displays and controls, same or different dynamics in each coordinate

Experimental Procedure

- Independent variables: **system order** (K, K/S, and K/S^2 for Figs. 1 and 2, and K and K/S for Fig. 3; CRef. 9.519)
- Dependent variable: root mean square error or **integrated error** expressed in arbitrary units
- Subject's task: track a cursor showing error on a CRT screen
- Highly practiced subjects

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Experimental Results

- Tracking error increases with control order, and this effect is influenced by multiaxis display/control configurations.
- A separated display/control configuration yields somewhat higher error than an integrated one (Fig. 1).
- **Rate** or **second-order control** yields the best performance in dual-axis tracking task (Fig. 2).
- When a zero-order task in one axis is paired with a higher-order task in the other axis (Fig. 2), performance deteriorates with increasing order (up to second order).
- When a first- or second-order task is paired with a task in another axis (Fig. 2), performance is best when dynamics are the same in both axes and deteriorates with greater difference in dynamics between the two axes. The difference is small when rate and acceleration are paired because of the general advantage of rate control.
- When like dynamics are paired in each of two dimensions (Fig. 3), integrated controls and displays are best and this effect is increased for acceleration (second-order) control.
- With like dynamics, display separation is more harmful than control separation (Fig. 3).
- With different dynamics, display and control separation both yield better performance than integrated displays and controls (Fig. 3).

Variability

No information on variability was given. Generally high with practiced operators.

Repeatability/Comparison with Other Studies

The results of the three studies illustrated in the figures support one another. A number of later studies have also supported the findings.

Constraints

- For a situation with similar dynamics in each coordinate, it is not clear that the benefit of display-control integration is enhanced with higher-order dynamics, because the advantage of integration is a constant ratio of root mean square error across orders.
- These results apply only to two-dimensional tracking tasks; three-dimensional (and higher) tasks present different problems for display-control integration or separation.

Key References

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Cross References

9.519 Control order;

9.533 Multiaxis separated displays;

9.534 Multiaxis separated displays: parafoveal tracking;

9.535 Multiaxis separated displays: scan patterns;

9.537 Multiaxis effects: extensions to more than two axes;

Handbook of perception and human performance, Ch. 39, Sect. 2.8

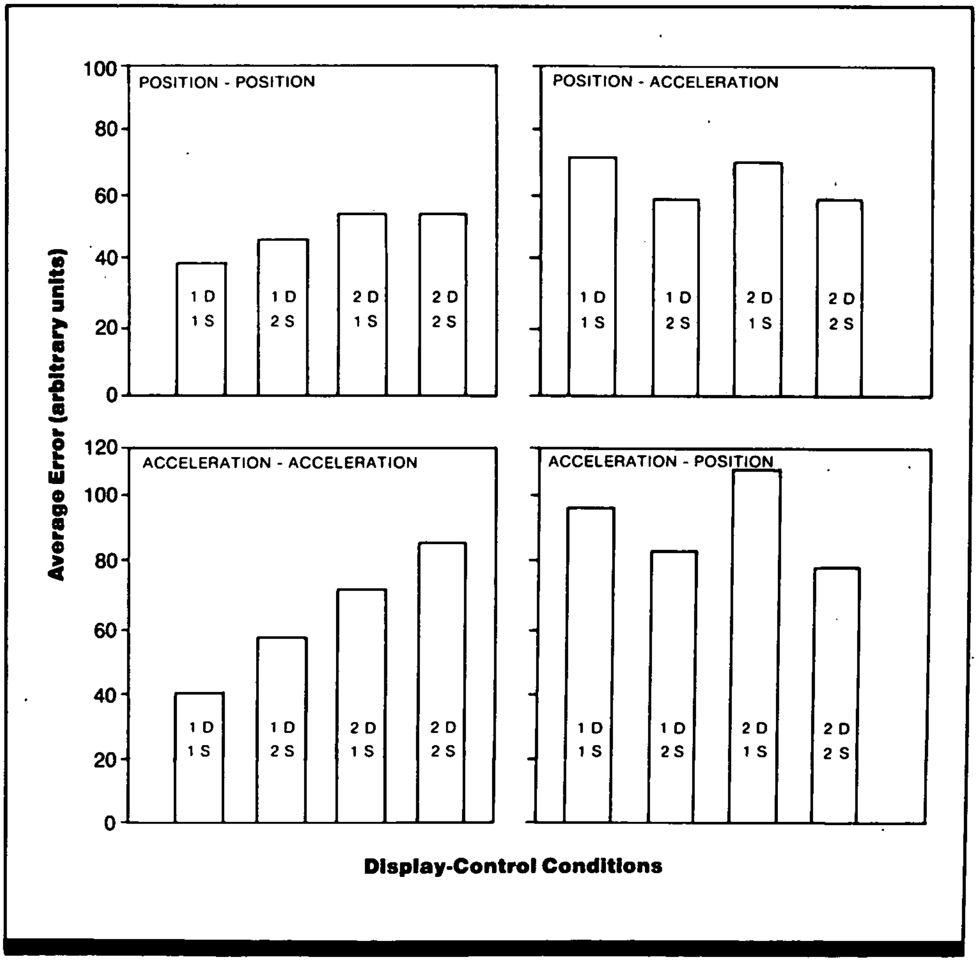

Figure 3. Tracking with paired same and different dynamics with separated and integrated displays. 1D and 2D indicate one and two displays, respectively; 1S and 2S indicate one and two controls, respectively. Error measured for dimensional list first in legend (at top left) for each panel. (From Ref. 3)

9.537 Multiaxis Effects: Extensions to More than Two Axes

Key Terms

Cooper-Harper rating; cross-coupling; feedback; force stick; integrated controls; mental models; side-arm controller; six DOF control; workload

General Description

Pilots and other vehicle operators must often control more than two axes of motion, such as pitch, roll, and yaw in a conventional aircraft, or the six degrees of freedom associated with spacecraft and helicopter control and some remote manipulators. Although a large volume of research is aimed at describing operator behavior in the continuous manual control task, as is reported in this volume and in Ref. 4, little information has been generated on specific effects of the extension of control to more than two axes.

Two studies (Refs. 1, 2), which investigated tracking performance in three- and four-axis tasks, found that performance in each axis deteriorated as more axes were added. However, the performance decrement was smaller with each additional axis, so that the total amount of information transmitted was greater. This suggests that there may be no upper limit to the number of axes that can be controlled, although accuracy decreases with each axis.

A task with 6 deg of freedom (three translational axes and three rotational axes) is of interest because this is the situation for spacecraft and helicopters. It would be advantageous to use a single, side-arm controller, especially in a contour-seated spacecraft; however it is not known if six degrees of freedom can be controlled with this type of integrated control. Studies with dual-axis control (CRef. 9.536) suggest that there is a strong interaction between display and control integration and control dynamics.

There is less uncertainty about the importance of proprioceptive feedback (i.e., feedback from the muscles about the position of the control); it is considered useful and necessary, although the particular characteristics of stick control (forces, gradients, damping, range of motion) depend on the particular task. The control should be transparent to the operator; that is, the operator should be able to predict the effects of control movements on the task (e.g., vehicle motion) at all times.

A force stick, or isometric control stick that responds to pressure rather than movement, is advantageous from an engineering point of view, especially for a side-arm controller; it is an effective controller in laboratory studies. Flight tests have failed to fulfill expectations, however, sometimes producing cross-talk or cross-coupling (CRef. 9.531), poor stick feel, and hand fatigue. This may be due to a lack of understanding of the application of this type of control to the particular task.

Control of more than two axes may be expected to produce an increase in pilot workload, which is generally measured by a post-flight questionnaire such as the **Cooper-Harper scale**. Other measures, such as **electromyograph (EMG) power spectra** and frequency of inputs of control reversals, may also be used. (The measurement of pilot or operator workload is a complex topic, discussed in detail in Ref. 4). The increase in workload as a function of the number of axes controlled is a topic that needs investigation.

Research on fast-running internal (mental) models of the system that the human operator acquires with experience may eventually prove useful in evaluating controller-system interaction in a tracking task, and should be applied to multiaxis tasks. Of particular interest is the optimal control model (CRef. 9.512) and the crossover model (CRef. 9.511).

Several alternatives to six-axis integrated controls have been tried, such as 2 x 3 deg of freedom, which requires both hands (therefore interrupted by other necessary activities), and foot controls, which are feasible, but slow and less accurate than hand controls. Such alternatives do not have the advantages of single-handed control, which allows simultaneous performance of other tasks (although at a cost in increased workload and decreased accuracy), and would perhaps allow a wounded pilot to save his and his crew's lives. Thus, it seems that some form of integrated six-axis control is necessary for certain vehicles. Its feasibility, however, is still in some question, although several six-axis controllers have been built in both laboratory and practical settings. It is quite likely that such controls will prove useful because of their advantages, but will present difficulties in terms of workload. They will have to be carefully designed to minimize problems such as crosstalk among axes and interactions of controls and displays with system dynamics.

Constraints

- Results to date on multiaxis control are mainly from experimental settings; care must be taken in extrapolating to real-world situations.
- The fact that more information is transmitted with multiaxis control does not mean that there is better control. In fact, the opposite is true: control in each individual axis gets worse. If control is lost in only one axis, total vehicle control may be lost, even though performance in all other axes is adequate.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

9.511 Modeling of the human operator: the crossover model;

9.512 Modeling of the human operator: the optimal control model;

9.531 Multiaxis and multiloop control: manual control with multivariate systems;

9.536 Multiaxis effects of control order

9.538 Non-Visual Displays

Table 1. Types of non-visual displays and their effects on performance in a tracking task.

Display Type	Effect on Performance	Applications
Auditory intensity		
Three-state auditory display: tone in right ear indicates error on right; left ear, error on left. Intensity proportional to degree of error	Tracking almost as good as visual equivalent with sine wave, 2-Hz input, slightly worse with complex 15-Hz input	Indicator of off-course heading for variable that does not require frequent adjustment, e.g., an emergency indicator
Tone in each ear indicates error; rate of interruption as a function of error size	Equivalent visual display much better	Redundant displays, auxiliary to same information displayed visually
Intensity of tone in left ear controlled to match that in right (pursuit) or fixed intensity tone in right ear, left-ear tone must also be kept fixed (compensatory) (CRef. 9.528)	Performance about three times worse than visual measured by time-on-target (CRef. 9.510)	Redundant displays
Relative intensity of tone in two ears controlled so it seems localized in center	Equivalent to visual tracking, but more easily disrupted by side task	Redundant displays
Auditory pitch		
Tone in each ear indicated error direction; higher pitch is greater error	Control of two independent axes better when one is visual and one auditory, rather than when both are visual	Vertical or short take-off and landing (V/STOL) situation; any situation with two independent axes (CRef. 9.533)
Tone in one ear, 500-1500 Hz; 1000 Hz is target, indicated by lower intensity; horizontal dimension presented visually	Audiovisual display gives less than half time on target of two-dimensional visual display	This type of auditory display not recommended
Two tones to be matched in pitch, presented either to one or both ears	Tracking better when both tones presented in both ears, so beats can be heard	Use only in situations with unidirectional error, since beats do not indicate direction
Pursuit display: match varying pitch of one tone with pitch of another. Compensatory: hold a pitch constant; reference tone needed only every 5-6 min	Compensatory better than pursuit	Redundant displays, or display on another axis with visual control of first axis
170-Hz tone shows down direction; 2300 Hz shows up; rate of interruption shows error size	Better than visual display when used with other visual displays at different distances	Airspeed indicator; any situation where visual workload is a problem
Cutaneous stimulation		
Three vibrators horizontally on chest; order of activation shows direction of turn; rate of repetition shows turn distance	Similar to performance with three lamps, after practice	Redundant displays
Other cutaneous displays	Tracking not as good as with visual display	
Kinesthetic and vestibular cues		
Control roll of simulated cockpit by vision alone, by perceived acceleration and tilt alone, or by two combined	Tracking same for three conditions at low frequency of divergence from stability; vision alone much worse at high frequency; combination best at high frequency. Tracking can be done using perceived tilt and acceleration alone, for pitch and roll	Situations where visual cues are absent

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Acceleration; audiovisual tracking; auditory display; auditory tracking; cutaneous displays; cutaneous tracking; multiaxis displays; tracking; vestibular tracking

General Description

Many visual controlling tasks have so many different visual inputs that it may be desirable to control some axes through other modalities (e.g., auditory signals); it is easier to divide attention between an auditory and a visual task than between two visual tasks. Studies seem to indicate that auditory displays, as well as some other non-visual displays, are valuable either as one of several (mostly visual) channels that must be processed, or as a redundant source of information in a primarily visual task. Table 1 summarizes several types of non-visual displays and includes performance results and possible applications for those displays.

Applications

Situations in which standard visual information channels are so overloaded that another means of presenting information about position is needed; situations where control with visual input is difficult and the addition of another channel aids tracking (a redundant display).

Constraints

- Use non-visual displays only if it is not possible to use a more conventional visual display in central vision.
- Displays that differ from those listed must be investigated before use.

Key References

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Cross References

3.106 Pressure and vibration sensitivity;

3.107 Vibrotactile stimulation: detectability of tactile pulses of varying duration;

6.501 Modes of display for two-dimensional multielement tactile patterns;

6.502 Factors affecting identification of tactile patterns;

6.508 Tactile versus visual recognition of characters;

9.510 Error, system control criteria, and human limitations in error control;

9.528 Pursuit versus compensatory displays;

9.533 Multiaxis separated displays

9.539 Effect of Practice on Tracking

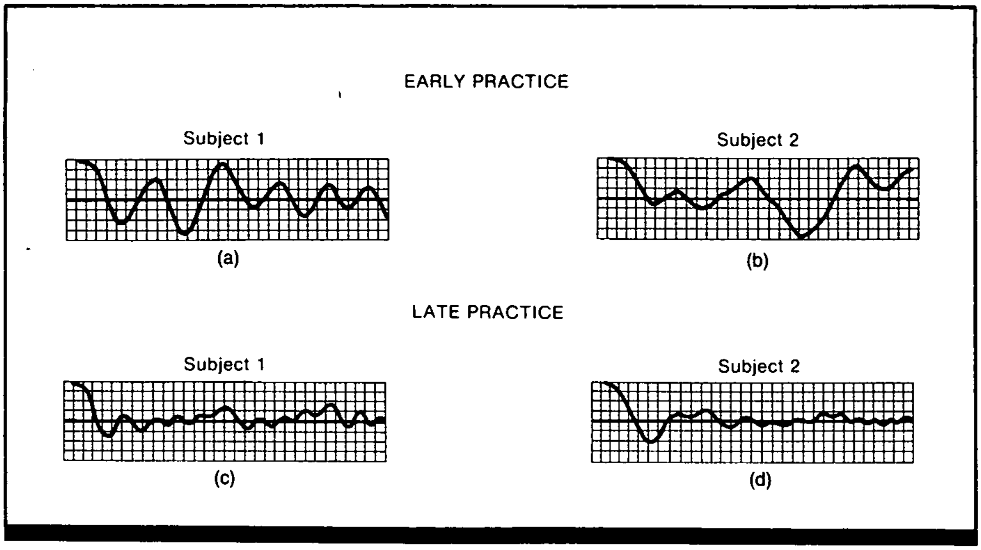

Figure 1. Records of displacement of target from center of screen showing effect of practice on temporal patterns of responses. Poor control and long interresponse intervals are shown for early practice (closed-loop mode); the left panel for late practice shows an open-loop pattern and the right pattern shows a modulation mode. (From *Handbook of perception and human performance*, based on Ref. 4)

Key Terms

Closed-loop; learning; practice; tracking; training

General Description

When subjects first attempt to operate a constant acceleration system (e.g., keeping an accelerating point centered on crosshairs), their performance suggests a closed-loop mode of operation. That is, the subject responds, waits for feedback about the results of the response, and then initiates a new response with corrections. The mean interresponse time is relatively long and effectiveness of control is poor and haphazard (Fig. 1a, b). As practice continues, one of two tracking behavior patterns develops: (a) an open-loop mode in which regular alteration of direction is occasionally stopped for correction (Fig. 1c), or (b) a modulation mode in which rapid alteration of direction is modulated by changing duration rather than by stopping for correction (Fig. 1d). The two strategies are not equally effective; it takes twice as much practice using the open-loop mode to achieve the modulation-mode level of performance. At all levels of learning, periods of highly organized responding are interspersed among periods of less systematic control.

Methods

Test Conditions

- Direction of continuously-moving target controlled by two keys, one to accelerate left and one to accelerate right; target to be centered on crosshairs on screen
- Keys pressed with index fingers; for Sessions 1-16, 40-g force needed to move key 2 mm; for Sessions 17-35, 130-g force needed to move 0.5 mm
- Subject listened to 70-dB white noise through headphones; interruption of white noise served as warning signal 2 sec before initial displacement of target from center to 5-cm marker on right; subject to press left key as soon as possible after initial displacement and then alternate key presses for ~6.4-sec trial
- For Sessions 1-16, acceleration constants of 7.62, 38.6, 94.5, 160, and 180 cm/sec^2 in either fixed (for first three and odd-number sessions) or random order; for fixed order, subjects knew which acceleration would be used for each block of 10 trials; for random order, trials randomized with each block; trial terminated if target overshot edge of screen
- 50-min session had five blocks of ten trials with 30-60- sec intertrial interval; one session per day for 16 days

Experimental Procedure

- Independent variables: acceleration value, fixed or random order, session number
- Dependent variable: integrated absolute error scores
- Subject's task: keep target centered on crosshairs by pressing left or right keys; error feedback given after each completed trial
- 5 male undergraduates with no practice

Experimental Results

- Subjects initially have poor control and long interresponse intervals, indicating a closed-loop response mode.
- Practice reduces the mean interresponse times and distinct temporal patterns of responses develop. This may indicate that sequences of responses are organized into larger units.
- Subjects who use an open-loop strategy and are slower learners achieve, with extended practice, performance levels similar to those of the other subjects.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

• The shape of the learning curve is almost identical for fixed and random orders of acceleration, and performance is affected only for the first response of a sequence.
• In general, rate of learning (Sessions 1-16) and amount of forgetting (Session 17) are directly related to the rate of acceleration.

Variability

Even in late practice, subjects could only maintain organized temporal patterns of responses for about half of the trial time. There were large individual differences in learning; 2 of the 5 subjects were slow learners.

Repeatability/Comparison with Other Studies

The hierarchical nature of the control of skilled acts develops with practice, beginning with strict closed-loop control and reaching levels of highly automatic action with occasional executive monitoring (Refs. 1, 3).

Constraints

• It is not clear whether the choice of strategy caused the slow learning of the slow subjects or the slowness of their learning caused the pattern of their control.
• The results described here could also be attributed to two closed loop modes, one mode in which subjects respond to target postition and a later mode in which they respond to position and velocity (Ref. 2).

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Cross References

9.202 One-versus two-handed reaching: effect of target distance and width;

9.206 Reaching hand movements: effect of varying visual feedback;

9.305 Coordination of hand movements on timed tasks;

9.402 Motor skill development with massed versus distributed practice;

9.502 Response of a gain element with pure time delay;

Handbook of perception and human performance, Ch. 30, Sect. 4.4

Notes

Key Terms

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Glossary

Bang-bang control. System control in which the operator moves the control stick rapidly from maximum deflection in one direction to maximum deflection in the opposite direction in a series of motions timed to bring the error to zero in a minimum time; used only when time constants are long or in acceleration (second-order) control systems (i.e.,when the system is sluggish in responding to a control input). (CRef. 9.524)

Bode plot. A plot in rectangular coordinates showing the magnitude of the input-output ratio of a system (in decibels) and the magnitude of the phase lag as a function of the logarithm of frequency.

Choice reaction time. The time from the onset of a stimulus to the beginning of the subject's response to the stimulus in conditions where there is more than one stimulus alternative and more than one response alternative. (CRef. 9.101)

Closed loop. A system in which the output (or some function of the output) is fed back and used to manipulate an input quantity so as to stabilize the system or achieve the desired control. Closed-loop systems are frequently called **feedback control** systems. (CRef. 9.506)

Command input. The motivating input signal to the system. An ideal tracking system will perfectly follow the command input.

Compensatory display. A display that shows the direction and magnitude of tracking error, but not the position of the input or system response independently of each other. (CRef. 9.528)

Compensatory tracking. Tracking in which the operator's display shows only the direction and magnitude of tracking error and does not independently present the command input and system position. The task is to compensate (correct) error.

Control/display ratio. For continuous control, the ratio of the movement distance of the control device to the movement distance of the display indicator (i.e., pointer or cursor).

Cooper-Harper Aircraft-Handling Characteristics Scale. A widely used rating procedure designed for use by test pilots in evaluating aircraft ease of control. Although the scale deals primarily with aircraft handling, several empirical studies have demonstrated a relation between scale ratings and subjective workload.

Course frequency. *See* **input frequency**.

Describing function. An engineering-mathematical description of a nonlinear system element as an equivalent element in which the relationships between some, but not necessarily all, pertinent measures of the input and output signals have "linear-like" features despite the presence of nonlinearities. This approach leads to a quasi-linear characterization of nonlinear elements that can be approximated by an equivalent linear element (the describing function) plus an additional quantity called the remnant.

Disturbance input. An undesired input signal that affects the value of the controlled output. In manual control, a signal arising from sources other than the operator's input or the command input track to be followed that affects the controlled output (e.g., turbulence or wind shear acting on an aircraft).

Electromyography. The recording and study of the electrical properties of the skeletal muscles.

Electro-oculography. The recording and study of the changes in electrical potential across the front and back of the eyeball that occur during eye movements; generally measured using two electrodes placed on the skin at either side of the eye. The electrical potential is a function of eye position, and changes in the potential are caused by changes in the alignment of the resting potential of the eye with reference to the electrodes.

Equalization. In control system design, the introduction of compensatory lead (prediction) and/or lag (smoothing) elements to achieve desired system response and stability.

Feedback. In a closed-loop system, the return of a part of the output of the system or mechanism to the input, so that dynamic response is made to the difference between input and output (i.e., the discrepancy between intended and actual operation) rather than to the input itself.

Feedback loop. *See* **feedback**.

First-order control. A system in which the response is proportional to the first time integral of the control input; also known as **velocity control**.

First-order dynamics. *See* **first-order control**.

First-order system. *See* **first-order control**.

Fovea. A pit in the center of the retina (approximately two degrees of visual angle in diameter) where the density of photoreceptors is highest and visual acuity is greatest.

Frequency domain specifications. For dynamic systems, expression of important system properties (i.e., speed of response, relative stability, and system accuracy or allowable error) as functions of frequency.

Gain. The ratio of output to input in a system; typically employed to specify, for example, the relation between control movement and display movement or system response. In the human describing function, it may also describe the relation between perceived error and controlled response.

Go/no-go reaction. A reaction time task in which the subject must respond ("go") when a given stimulus is presented but must not respond ("no go") on trials on which any other (or no) stimulus occurs.

Head-up display. A display in which information is viewed superimposed on the outside world (as by displaying on a windscreen or visor) so that the information can be read with the head erect and with the outside world always in the field of view.

Input frequency. The frequency of the changes a system is supposed to follow; the frequency of the forcing function or desired path when only one frequency (a pure sine wave) is present.

Inside-out display. A display (as of aircraft attitude) that uses the vehicle as a frame of reference, so that the display reflects the way the environment appears to the operator inside the vehicle looking out. For example, when the aircraft banks, the horizon in the attitude display tilts. (CRef. 9.529)

Integrated error. Tracking error that is summed over the tracking task.

Lag time constant. For first-order (exponential) lag, the time required for the output to reach 63% of its final value in response to a step input. It generally describes the "responsiveness" of the system, with sluggish systems having long time constants.

Laplace domain. *See* **Laplace transform**.

Laplace operator. *See* **Laplace transform**.

Laplace transform. A transformation technique relating time functions to frequency-dependent functions of a complex variable.

Lead time constant. The time constant of a lead element placed in a dynamic control loop to increase high-frequency stability. It determines the frequency above which the system responds with lower order.

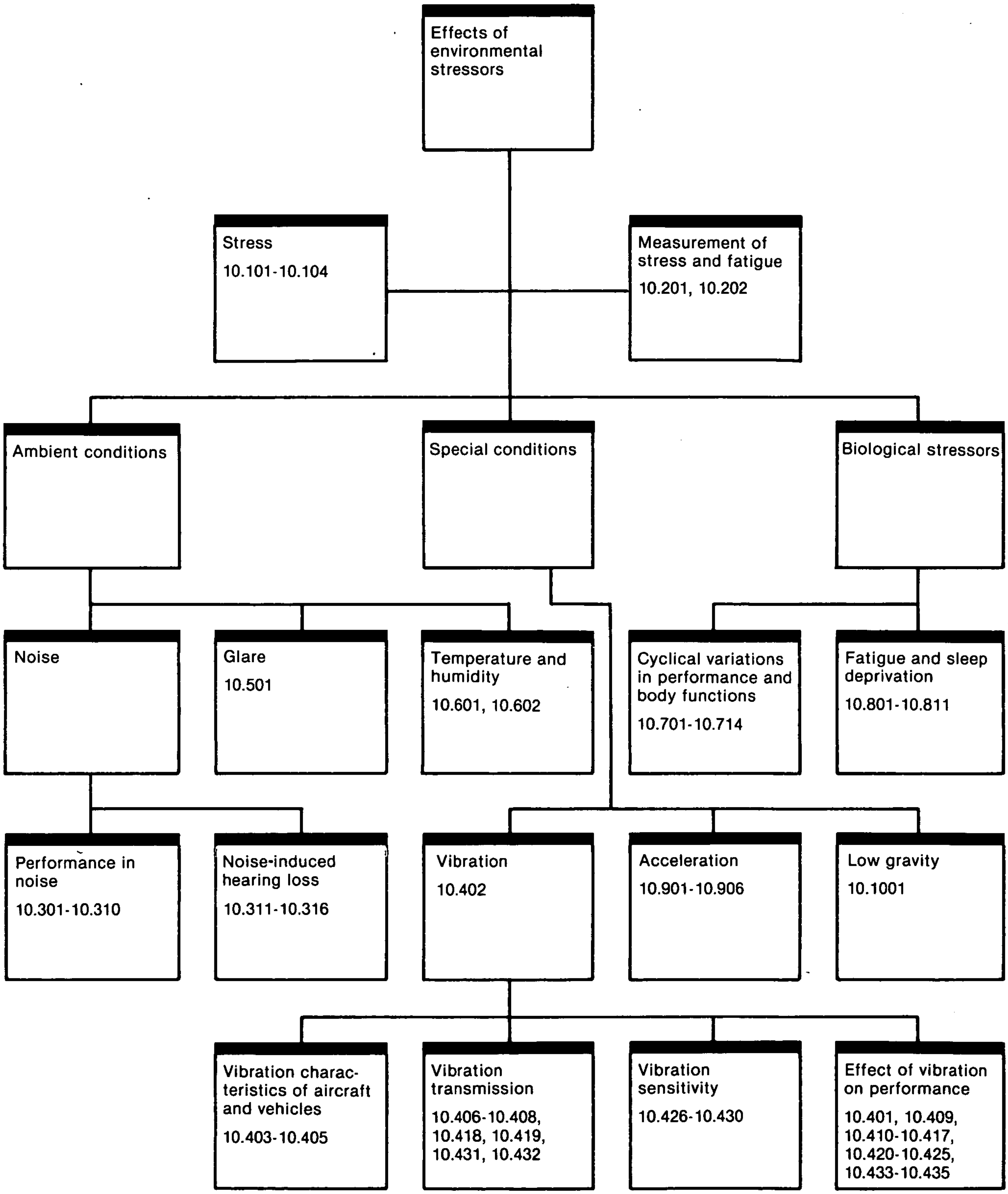
Medial plane. The vertical plane passing through the middle of the body from front to back and dividing the body into left and right. Sometimes called **sagittal plane.**

Negative feedback loop. A feedback loop in which a signal from a part of the system following the control is fed back to the system input with a polarity opposite to that of the control output, thus tending to decrease output and helping to stabilize the system by avoiding progressively increasing error.

Open loop. A system in which there is no feedback of information about an output to an earlier stage of the system. (CRef. 9.506)

Order. *See* **system order.**
Parafovea. A region of the retina covering approximately 4 deg of visual angle (0.5 mm), immediately surrounding the fovea.
Performance operating characteristic. A curve showing how performance on one task varies as a function of performance on a second task when the two are carried out concurrently and the relative emphasis on one task or the other is varied; that is, a performance trade-off function describing the improvement in the performance on one task due to any added resources released by lowering the level of performance on another task with which it is time-shared. (CRef. 7.205)
Phase droop. The increased phase lag at very low frequencies that is sometimes observed in the human operator manual control response.
Position control. A control system in which the output position is directly proportional to the input position. (*See also* **zero-order control.**)
Power spectrum. A plot of the distribution of intensity as a function of frequency (with frequency usually given in logarithms). Also called **power density spectrum** and **frequency spectrum.**
Pursuit tracking task. Tracking in which the operator's task is to keep a marker or cursor on a moving target symbol or command input; the operator chases or pursues the target with the target position always displayed and the size and direction of tracking error available from the positions of the target and marker or cursor.
Quickening. A display technique in which the higher derivatives of the error (or system state) are added directly onto the error position with some relative weighting; that is, the rate at which error is changing, and higher derivatives as well, are represented as additions to the deviation of a cursor from a reference position in the display. Quickening is used to reduce the difficulty of controlling higher-order systems. (CRef. 9.525)
Random walk model. A model of the perception and decision response components in reaction time tasks. According to the model, an ideal detector accumulates information about the identity of the stimulus from the start of a trial; when the information exceeds some preset threshold (response boundary), the appropriate response is made. Each new increment of information takes a constant time and is assumed to be somewhat unreliable so that the cumulative balance of all the information waivers (i.e., executes a random walk) between the alternatives.
Rate-aided system. A position control system to which a rate control system has been added.
Rate control. *See* **first-order control.**
Rate order. *See* **second-order control.**
Reaction time. The time from the onset of a stimulus to the beginning of the subject's response to the stimulus by a simple motor act (such as a button press).
Remnant. In a quasi-linear characterization of a nonlinear system, the component that represents the difference between the response of the actual nonlinear system and the equivalent linear element (the describing function); called "remnant" because it is left over from the portion of the system response represented by the linear element.
Roll angle. The angle of rotation about the longitudinal (nose-to-tail) axis of an aircraft.
Second-order control. A system in which the response is proportional to the second time integral of the control input; also called **acceleration control.**
Second-order system. *See* **second-order control.**
Sine-wave grating. A bar pattern in which some property (generally luminance) varies with spatial position according to a sine function in a direction perpendicular to the bars. (CRef. 1.601)
Spatial frequency. For a periodic target, such as a pattern of equally spaced bars, the reciprocal of the spacing between bars (i.e., the width of one cycle, or one light bar plus one dark bar), generally expressed in cycles per millimeter or cycles per degree of visual angle.
System order. For a control system, the highest power of the Laplace operator, *S*, that appears in the denominator of the transfer function. Equivalently, the order of the highest-order derivative of the differential equation describing the system element. (CRef. 9.519)
Third-order control. A system in which the response is proportional to the third time integral of the control input.
Third-order system. *See* **third-order control.**
Time constant. *See* **lag time constant; lead time constant.**
Transfer function. A complex function describing a dynamic system as a function of frequency that specifies the ratio of output to input amplitude and the phase difference between input and output.
Transmission lag. Pure time delay, i.e., a delay (expressed in time units) in transmitting input to output that leaves all other aspects of the signal unchanged.
Velocity control. *See* **first-order control.**
Visual angle. The angle subtended at the eye by the linear extent of an object in the visual field. It determines linear retinal image size. (CRef. 1.240)
Zero-order control. A system in which the position (or zero time derivative) of the response is proportional to the control input position; also called **position control.**

Organization of Entries



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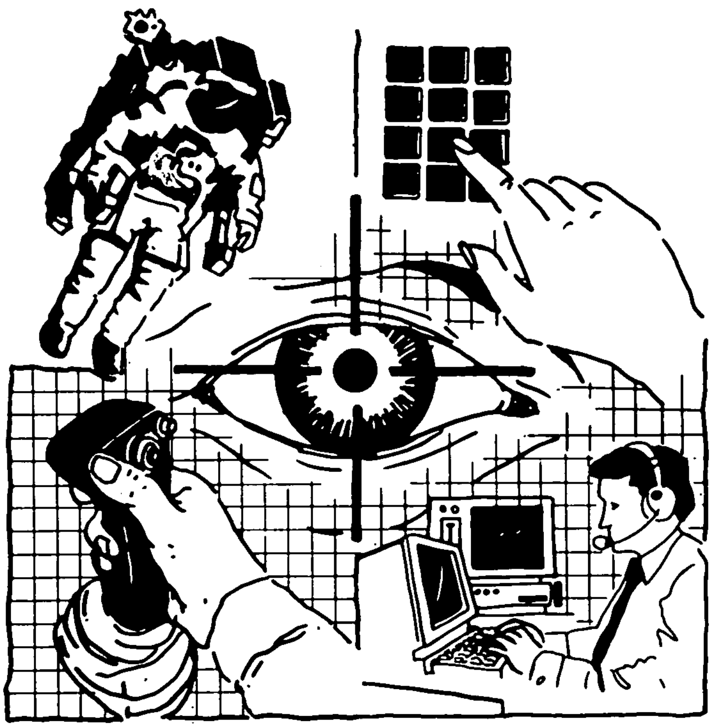
Section 10.0 Effects of Environmental Stressors



10.101 Theories of Arousal and Stress

Key Terms

Adaptation syndrome; arousal; attention; drive; motivation; Yerkes-Dodson law

General Description

Determinants of action, or those processes which initiate or energize behavior, have been conceptualized under the theoretical constructs of drive, motivation, stress, and arousal. All of these concepts assume a unitary, nonspecific process which determines the intensity of behavior.

Stress

Selye (Refs. 6, 7, 8) presented the first discussion of stress, noting that several different noxious events could produce one fairly consistent, somatic, endocrine response. Selye considered the body's reaction an adaptive one in the face of a threat, and named it the general adaptation syndrome (GAS). Since Selye's conceptualization, the term stress has been used to characterize unusual conditions of work or the behavior associated with those conditions.

Arousal

The early investigations of arousal, or the relationship between energy mobilization and performance efficiency, focused, for example, on muscle tension and reaction time (Ref. 2). Interest in this concept grew after EEG differences as a function of behavioral alertness were demonstrated. Arousal became a central concept of behavior; Hebb (Ref. 4) equated it with drive.

The most widely accepted view of arousal is conceptualized in the Yerkes-Dodson law (CRef. 10.104), which states that there is a non-linear relationship between stress and performance. Performance is related to arousal in an inverted-U function, being best at an intermediate arousal level. The optimum level of arousal is inversely related to task difficulty. Easterbrook (Ref. 3) suggests that increased arousal restricts the range of events that we can process. At low levels of arousal, our attention to task-irrelevant cues is diminished; at higher levels of arousal, however, task-relevant cues are also ignored. Easterbrook's (Ref. 3) hypothesis, that arousal causes an increase in selectivity, is the widely accepted hypothesis, although few studies have been conducted which manipulate arousal level and task difficulty.

Information Processing

A third theoretical approach uses an information processing model to measure and interpret the effects of stress. The model assumes that behavior is best considered in terms of the processing of information, rather than associations between stimuli and responses. Efficiency of processing may be inferred from speed and accuracy of task performance. Derived from general principles of communications engineering and cybernetics, the main information processing theory components are input processes, output processes, storage processes, a central processor, and attention. Research in this area illustrates that humans are capable of regulating their behavior to minimize the effects of distractors. Inefficiency can be minimized when a task requires responses on a predictable schedule or with long interresponse times; Broadbent (Ref. 1) suggests that, to detect brief interruptions in task information processing, tasks should present information infrequently, at unpredictable times, at a high rate, or over a long period of time.

More recently, the information processing model has been influenced by the computer. There has been an increased concern with strategies; cognitive processes are more emphasized than is the study of inputs and outputs.

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Cross References

7.804 Effects of stress on performance for introverts and extroverts;

10.103 Classification of factors influencing the stress state;

10.104 Arrousal level: effect on performance;

10.201 Types of tasks used in measuring the effects of stress, fatigue, and environmental factors on performance;

10.202 Effects of different stressors on performance;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.807 Sleep deprivation: use of physiological indicators to predict performance decrement

Notes

10.102 Environmental Stress, Fatigue, and Circadian Rhythms

Key Terms

Arousal; circadian rhythm; drive; endogenous rhythms; exogenous rhythms; fatigue; infradian rhythms; Mackworth clock test; memory; sleep; speed-accuracy tradeoff; tracking; ultradian rhythm; vigilance; work shifts

General Description

Environmental stress, fatigue, and cyclical fluctuations in bodily processes affect human performance. Noise, heat, anxiety, fatigue, shift work, and jet travel, for example, alter the state of the body independent of the specific demands of the work being done. Yet, these induced states may have important consequences for the quality of that work, as well as for our understanding of the processes involved in its execution.

Research in the area has origins in two distinct kinds of problems. The first concerns the specific needs of applied situations where the object of the research is primarily to find practical solutions, often with only short-term applications. The second source of stress research is more theoretical, and is concerned with understanding the way in which information processing is affected by changes in the state of the individual. These two approaches sometimes produce results that appear inconsistent.

Historical Development

Interest in the implications of general properties of the energetic state of the organism for the efficiency of behavior goes back to some of the earliest work in experimental psychology. At least three separate theoretical notions can be identified: drive, stress, and arousal. The concept of drive refers to the development of a generalized motivational state arising out of the activation of specific needs. This idea has been almost entirely absorbed within the current arousal or activation theories. Stress was first discussed in the context of endocrinology, but was expanded to include all the somatic reactions responsible for the adaptive bodily response to threat (general adaptation syndrome). More generally, stress has come to be used to refer to any unusual state or condition of work, or to the behavior pattern associated with the state or condition.

The third concept, arousal or activation, became generally accepted as a central feature of all behavior and was equated with drive. Underlying most arousal concepts is the idea of a unitary, nonspecific process responsible for the intensity of bodily or behavior function, but it now seems clear that this cannot be true in any simple form.

Classes of Stressors

The classes of stressors usually studied are:

- Physical conditions, such as noise, vibration, or heat
- Social influences, such as anxiety or incentives
- Drugs, such as tranquilizers or alcohol
- Fatigue states, such as result from overwork or sleep loss
- Cyclical changes, such as the sleep/work cycle or body temperature rhythm, often studied by disruption of the rhythm.

Of the five categories of stressors, the cyclical changes category differs from the other four in that it is studied in two ways: one by measurement in normal conditions, and the other by causing some form of disruption of the usual rhythm. Rhythms having a period shorter than the solar day, such as the 90-min rapid eye movement (REM) sleep stage, are called **ultradian** rhythms, while those longer in period than the solar day, such as menstruation, are called **infradian**. The circadian (20-28 hr) rhythms are the most frequently studied and are disrupted by: shift work, jet travel, isolation from all cues to time of day (free running), and isolation from natural clues so that schedules can be arbitrarily manipulated.

Data from physiological or performance measures are fitted to a cosine curve to establish the characteristic of the particular biological rhythm. Constant monitoring of the measure following schedule disruption allows the adaptation to the shift to be studied. The purpose of this disruption is to explore the cause of the rhythm. Endogenous rhythms, those generated by an internal regulator, are slow to adapt to change of schedule, while exogenous rhythms, those caused by outside forces, adapt more rapidly and/or more completely to schedule change.

Tasks and Performance Measures

Certain tasks have been found to be more susceptible than others to the effect of stressors, and are most commonly used in this research:

- Vigilance, such as the Mackworth clock test
- Serial reaction, self-paced tasks, such as the five-choice serial response task
- Tracking, which is similar to driving
- Visual search
- Memory tasks, such as digit span or immediate recall

as well as more complex tasks which are susceptible to speed/accuracy trade-offs, allow separation of processing strategies, or require selective attention.

Certain performance measures more reliably show the effect of stressors than do others:

- Alertness (typical of high or low arousal)
- Selectivity or degree of attentional narrowing
- Speed (rate of work in a continuous task)
- Accuracy (in a continuous task may be traded off with speed)
- Short term memory capacity (STM)

Different patterns across these measures result from different stressors. Although there are two patterns which seem generally to characterize global states of high or low arousal, there is variation within these patterns, suggesting that arousal or activation is made up of several components.

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Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Summary

Although single-mechanism theories of arousal long dominated stress research, the use of more complex tasks and of patterns across performance measures (as well as the simultaneous recording of many physiological parameters) reflects a trend toward considering multiple mechanisms in arousal and their complicated interaction with other variables in humans and their environment.

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Cross References

7.801 Effect of incentives on performance;

7.803 Effect of anxiety on performance;

10.101 Theories of arousal and stress;

10.103 Classification of factors influencing the stress state;

10.201 Types of tasks used in measuring the effects of stress, fatigue, and environmental factors on performance;

10.202 Effects of different stressors on performance;

10.701 Characteristics of biological rhythms;

10.703 Cyclical patterns of sleep;

10.707 Circadian variation in work efficiency;

10.709 Ultradian rhythms

10.103 Classification of Factors Influencing the Stress State

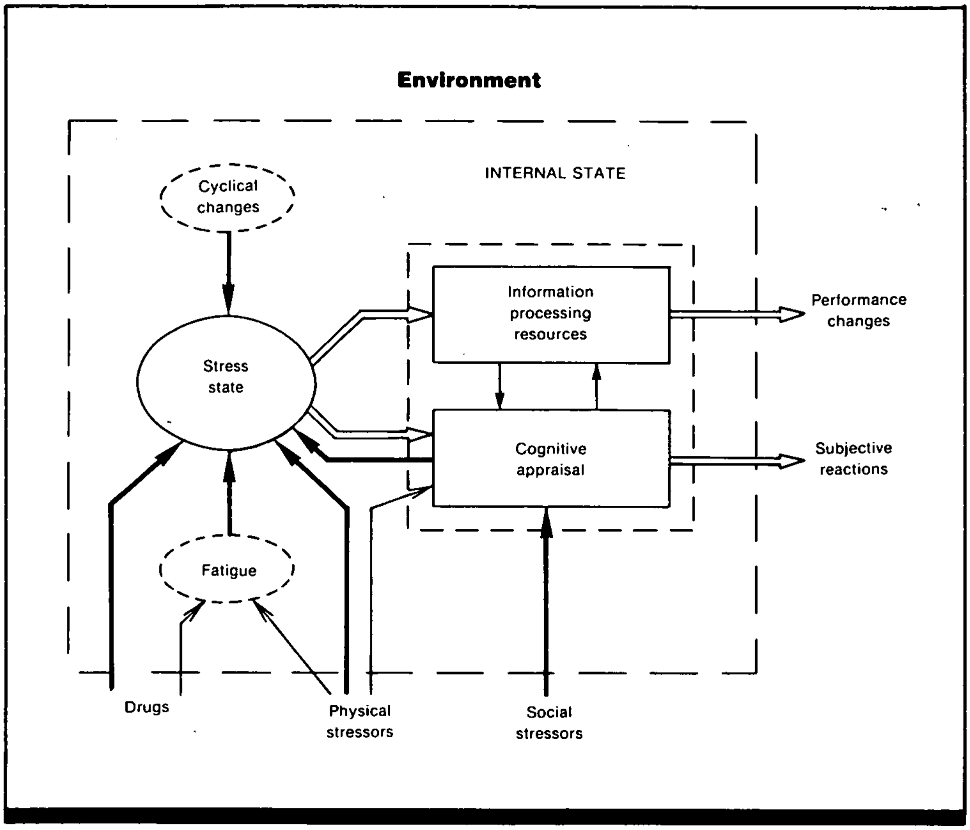

Figure 1. Functional relationships among different classes of stress variables. Primary effects are shown as heavy solid arrows, secondary effects as lighter solid arrows, and effects of the stress state on behavioral variables as open arrows. (From Ref. 1)

Key Terms

Alcohol; anxiety; body temperature; circadian rhythm; cold; fatigue; heat; incentive; motivation; noise

General Description

Figure 1 shows functional relationships among different classes of stress variables.

Internal/External Origin of Stressor

The general concept of stressor, defined as any change in bodily state that can cause changes in performance, encompasses states imposed on individuals as well as conditions arising from their natural dynamic system. Noise is a physical stressor. The effect of noise on performance can be reduced if we believe we can control the noise, so cognitive appraisal or mediation can directly affect physiological manifestations of a stress state. Changes brought about by circadian fluctuations in the level of various biological functions should perhaps not be called stressors. For example, the low point in the circadian rhythm of body temperatures causes neither cognitive nor physiological stress in the individual who is asleep, but it may cause subjective appraisal of fatigue and/or performance deficits for night-shift workers obliged to stay awake and concentrate on a task, especially a simple repetitive task, during the period

Transient/Sustained Stressors

Little is known about the long-term consequences of exposure to stress. Noise as a stressor has been studied under laboratory conditions in which subjects are exposed to a 30-min work period in 85 dB noise. However, the effect might be very different for individuals performing the same task over a period of months in an office situated beneath a major flight path where the same noise level exists. An example of an internal, sustained stressor is anxiety, which is an almost permanent condition for some individuals (for others it is a temporary response to particular social circumstances).

The table categorizes stressors, gives examples (with the most frequently researched in boldface), briefly describes the stressor along the internal/external dimension, and lists variables which are known to interact with the stressors.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Hockey, G. R. (1986). Changes in operator efficiency as a function of environmental stress, fatigue, and circadian rhythms. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol II. Cognitive processes and performance*. New York: Wiley.

Cross References

7.417 Effect of boredom on detection efficiency;

7.801 Effect of incentives on performance;

7.802 Situational stress: effects of personality type and threat;

7.803 Effect of anxiety on performance;

7.804 Effects of stress on performance for introverts and extroverts;

10.302 Continuous broadband noise: effect on task performance;

10.601 Heat: effect of exposure duration on task performance;

10.602 Cold: effect on performance;

10.707 Circadian variation in work efficiency;

10.709 Ultradian rhythms;

10.710 Adaptation of circadian rhythms to altered schedules;

10.712 Schedule shift: effect on performance;

10.713 Rapid time-zone shifts: effect on performance and body temperature;

10.714 Sleep/wake and body temperature cycles during isolation from external time references;

10.801 Fatigue: effect on performance;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.809 Partial deprivation of sleep: effect on performance;

Class of Stressor	Examples	Mode of Effect	Interacting Variables	Sources
Physical	**Heat**/cold, **noise**/vibration, lighting conditions, atmospheric conditions	Direct effect on central nervous system via changes in sensory receptors	Individual differences, task, possibility of control, other stressors	CRefs. 7.804, 10.302, 10.601, 10.602, 10.805
Social	**Anxiety, incentives**	Cognitive mediation	Individual differences, type of task, presence of other stressors	CRefs. 7.801, 7.802, 7.803, 7.804, 10.805
Drug	Medical (tranquilizers), social (caffeine, nicotine, **alcohol**)	Direct effect on central nervous system	Individual differences, task, other stressors	CRefs. 7.804, 10.805
Fatigue	Boredom, **fatigue, sleep deprivation**	Both direct physiological and cognitive mediation	Individual differences, type of task, time of day, other stressors	CRefs. 7.417, 7.804, 10.801, 10.805, 10.809
Cyclical	**Sleep/wake cycle, body temperature rhythm**, other physiological rhythms; usually studied are disruptions of the rhythms by **shift work, transzonal flight**	Some are dependent on environmental changes; others seem internally driven	Individual differences, task, form of the disruption	CRefs. 7.804, 10.707, 10.709, 10.710, 10.712, 10.713, 10.714, 10.805

10.104 Arousal Level: Effect on Performance

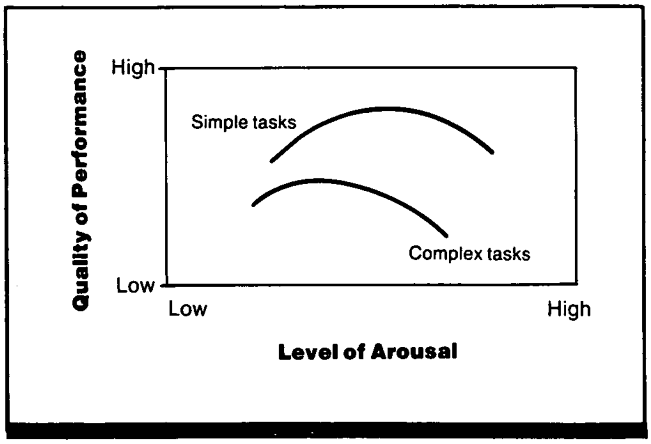

Figure 1. Performance as a function of arousal level for simple and complex tasks. (From Ref. 2)

Key Terms

Arousal; attention; motivation; Yerkes-Dodson law

General Description

Arousal (or motivation, drive, stress) affects performance in a nonlinear manner, as was first demonstrated by Yerkes and Dodson (Ref. 4). Level of arousal was defined as various intensities of shock delivered to mice after incorrect responses in a discrimination task. Task difficulty was also varied. For the easiest discrimination task, performance was best at the highest intensities of shock. For more difficult tasks, performance was best with low shock intensity. The two principles of the Yerkes-Dodson "law" are:

1. Performance and arousal are related in the form of an inverted-U function; performance is best at some intermediate level of arousal (Fig. 1).

2. The optimum arousal level is inversely related to task difficulty.

The relationship between arousal and performance was popularized by Easterbrook (Ref. 1), who used it to account for observed inconsistencies in the effects of arousal level on behavioral efficiency. Easterbrook proposes that the inverted-U function can be explained in terms of selectivity, or a narrowing of attention to cues. At low levels of arousal, the effect diminishes attention to task-irrelevant cues and thus enhances performance. The selectivity caused by high levels of arousal, however, leads to neglect of task-relevant cues, and degrades performance.

Few studies have manipulated both arousal level and task difficulty, so evidence supporting Easterbrook's hypothesis is indirect.

Key References

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4. Yerkes, R. M., & Dodson, J. D. (1908). The relation of strength of stimulus to rapidity of habit formation. *Journal of Comparative and Neurological Psychology, 18,* 459- 482.

Cross References

7.803 Effect of anxiety on performance;

10.101 Theories of arousal and stress;

10.103 Classification of factors influencing the stress state;

10.201 Types of tasks used in measuring the effects of stress, fatigue, and environmental factors on performance;

10.202 Effects of different stressors on performance

Notes

10.201 Types of Tasks Used in Measuring the Effects of Stress, Fatigue, and Environmental Factors on Performance

Key Terms

Arousal; attention; Mackworth clock test; memory; noise; pursuit eye movements; recall; selective attention; serial responding; signal detection; speed-accuracy tradeoffs; stress; target acquisition; tracking; vigilance; visual search

General Description

Human beings are capable of self-regulating behavior and can avoid performance degradation in the face of stress, fatigue, and such environmental factors as noise or heat. On tasks with long rest pauses between responses, when responses are required at predictable times, such compensation can effectively mask the effects of stress or fatigue. The table describes tasks that are frequently used to assess the effects of stressors on human performance, the performance measures employed, the characteristics of the task which make it susceptible to stressor effects, and the manipulations that have made it useful. The categories are not mutually exclusive, and combinations of tasks are sometimes studied.

Task	Typical Description	Task Demands	Performance Measures	Manipulations	Source
Vigilance	The Mackworth Clock Test employs a clock face around which a single pointer moves in discrete steps. Signal targets are a double-size jump of the pointer. (Many other vigilance tasks using visual or auditory signals are employed)	Signals at unpredictable intervals Infrequent signals Long test session (2 hr)	Correct detection of signal target (hit rate, detection %) Other measures allow separation of sensitivity and decision criteria (see Separation of processing strategies below): incorrect detections (false alarm rate), omission errors (misses), and/or reaction times	Signal rate, session length, and number of clock faces can be changed (see Selective attention) Signal cueing can be added	CRef. 10.303
Serial reaction	The five-choice serial reaction task uses five neon bulbs forming a pentagon; each bulb's circuit can be closed by the touch of a stylus. The signal target is a lighted bulb. Touching any circuit alters the display; the lights are randomized, and each stays lighted until a circuit is closed	High rate of information (each response is followed immediately by a new signal requiring a decision) No rest pauses	Work rate (number of decisions made in a given time) Errors (number of incorrect responses) Gaps (number of very long response times)	Number of lights can be varied, but usefulness of task is greater for its continuous performance demand than for its potential for variation	CRef. 10.805
Tracking	The most common version, pursuit tracking, requires the subject to control an object pointer, maintaining alignment with a moving target pointer, such as in steering a car	High rate of information (requires even more continuous attention than serial reaction does) No rest pauses	Time on target (TOT) Integrated measures of error magnitude	Often combined with a second (vigilance) task to measure selective attention Like serial reaction, the usefulness of the task is greater for the continuous performance demand than for its potential for variation	CRef. 10.304

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Task	Typical Description	Task Demands	Performance Measures	Manipulations	Source
Visual search: vigilance type	Simulation of air traffic control radar unit is typical. Blips representing aircraft are identified by six alphanumeric characters where first two letters designate the aircraft, three numbers indicate altitude, and final symbol indicates either maintaining correct altitude (nonsignal target) or departure from correct altitude (signal target)	Signals at unpredictable intervals Infrequent signals	Mean response time (search time) Standard deviation of latency (variability) Differential response time and errors for signal targets by area in the visual field	Density of non-signal targets (number of targets per area), size of search area, and signal target rate can be changed Visual field placement of signal targets can be manipulated	CRefs. 7.417, 10.712
Visual search: memory type	Subject searches an array for one or more symbols; for example, letters between A and M, while distractor items are letters from N to Z or numbers		Reaction time to positive and negative responses (with manipulation of the variables) allows analysis of the search process as serial or parallel, self-terminating or exhaustive Speed of comparison processes	Number of symbols to be searched for can be changed The differences between target items and distractors can be increased or decreased, depending on letters or numbers chosen	CRefs. 7.417, 10.712
Memory search	Subject learns a list and then scans that list for the presence or absence of a target item (similar to Visual search: memory type)		Reaction time to positive and negative responses (with manipulation of variables) allows analysis of the search process as above Speed of comparison processes	Number of symbols to be memorized can be changed	
Memory	a. Immediate recall: a list of digits or words is presented and subject must recall the list b. Cognitive: the letter transformation task is often used. Mental calculations are used such as: add three to G (answer J) or add two to DKT (answer FMV) c. Delayed recall: stories, word lists, or sentences are presented, subject recalls as much as possible hours or days later	Manipulation of variables permits analysis of the structure of memory (relation of short-term/long-term), the nature of coding used in storage, capacity of the system, and point where stressor has effect	Percentage correct Patterns of errors	a. Size of list and type of symbol on list (digit, word) can be changed Time stressor applied can be varied b. Size of memory load or processing difficulty can be changed Time stressor applied can be varied c. Type of material used can be changed Time stressor applied can be varied	CRef. 10.811 CRef. 10.309 CRef. 10.810

(Continued)

Task	Typical Description	Task Demands	Performance Measures	Manipulations	Source
Selective attention	a. Process one source: dichotic listening (attend to and report only what is heard in one ear)	a. Need to allocate attention differentially	a. Percentage correct Patterns of intrusion errors	a. Differential intensity between sources Differential content between sources	
	b. Favor one, process both as in dual task: primary task (tracking) keep pointer on target; secondary task (vigilance) report light flashes of six lamps peripheral to tracking window	b. Need to allocate attention differentially	b. Time-on-target for tracking Correct detections for vigilance Response latency for vigilance	b. Definition of importance of each task	CRef. 10.304
	c. Process all: monitor three machines for fault state, detectable only by direct sampling of one source at a time	c. Need to divide attention	c. Differential correct detection or latency for various sources	c. Spatial placement of sources Differential intensity of sources (such as varied signal probabilities)	CRef. 10.307
Speed/ accuracy tradeoffs	Many of the tasks listed above have been used, particularly the five-choice serial-reaction task		Work rate (number of decisions made in a given time) Errors (number or percent of wrong responses) Gaps (number of very long response times)	Comparison of speed relative to accuracy under different conditions	CRef. 10.305
Separation of processing strategies	Many of the tasks listed above have been used. One example is the Mackworth Clock Test, where information about correct detections, omissions, false alarms, and correct negatives is analyzed according to signal detection theory to differentiate changes in performance caused by a sensitivity decrement and those caused by a change in the decision criterion employed In this example, a response format would have to be used so that both positive and negative detections of the signal target were reported. (In examples, such as memory or visual search, a method of analyzing the results which permits separation of the component processes would have to be used)		Correct detection of signal target (hits) Correct rejection of non-signal target Incorrect detection (false alarm) Omission errors (misses)	The most frequent manipulation for signal detection analysis requires confidence ratings for responses, but instructions to use risky or cautious criteria and manipulation of the payoff matrix are also used	

Key References

*1. Eysenck, M.W. (1982). *Attention and arousal: Cognition and performance*. Berlin: Springer-Verlag.

Cross References

7.410 Maintenance of vigilance level by adaptive changes in signal detectability;

7.411 Characteristics of the task that affect vigilance, monitoring, and search;

7.417 Effect of boredom on detection efficiency;

7.803 Effect of anxiety on performance;

10.303 Continuous broadband noise: effect on vigilance performance as a function of number of monitored sources;

10.304 Continuous noise: effect on a dual vigilance task;

10.305 Continuous open-field white noise: effect on speed/accuracy tradeoffs in serial response tasks;

10.307 Continuous noise: effect on sampling of signal sources;

10.309 Continuous noise: effect on performance of a letter-transformation task with varying memory load;

10.712 Schedule shift: effect on performance;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.810 Selective sleep deprivation: effect on memory;

10.811 Partial sleep deprivation: effect on vigilance and cognitive performance

10.202 Effects of Different Stressors on Performance

Table 1. Effects of different stressors as measured by five behavioral indicators.

Stressor	Alertness	Selectivity	Speed	Accuracy	Short-term Memory	Source
Noise	increase	increase		decrease	decrease	Refs. 3, 4, 5, 6, 8, 9
Anxiety	increase	increase		decrease	decrease	Refs. 5, 13
Incentive	increase	increase	increase	increase	increase	Refs. 3, 5, 6
Stimulant drugs	increase	increase	increase		decrease	Refs. 3, 5, 15
Later time of day	increase	?	increase	decrease	decrease	Refs. 1, 3, 5, 6, 7, 9
Heat	increase	increase		decrease		Refs. 3, 5, 12
Alcohol	decrease	increase	decrease	decrease	decrease	Refs. 3, 5, 8, 9, 15
Depressant drugs	decrease	decrease	decrease	decrease	decrease	Refs. 3, 5, 11, 15
Fatigue	decrease	increase	decrease	decrease		Refs. 3, 5, 10
Sleep loss	decrease	decrease	decrease	decrease		Refs. 3, 5, 6, 8, 9
Earlier time of day	decrease	?	decrease	increase	increase	Refs. 1, 3, 5, 6, 7, 9

Key Terms

Alcohol; anxiety; depressant drugs; fatigue; heat; incentive; memory; noise; short-term memory; sleep deprivation; stimulant drugs; stressors; time of day

General Description

The effect of stress on human performance does not follow a single pattern; different stressors produce effects on different performance measures (CRef. 10.805). Since different tasks use different performance measures, the development of a taxonomy of behavioral indicators would permit cross-task comparisons of the stress state. No comprehensive taxonomy of behavioral indicators has been agreed upon, but five have been suggested: general alertness (assessed by physiological and/or subjective measures), selectivity (difference between performance measures for separate portions of the task), speed (calculated from correct and incorrect responses), accuracy (proportion of responses that are correct), and short-term memory capacity (inferred from memory or from performance on a memory-related task).

The effects of different stressors across the behavioral indicators are shown in the table. The upper and lower halves of the table show overall patterns consistent with high and low arousal, respectively. There are, however, considerable variations within each of these general patterns.

Empty cells indicate either no change in, or no consistent trend across studies for, that indicator. A question mark is used to indicate cells where there is insufficient data.

Constraints

- The pattern noted here may vary if an applied task is very different from those studied.
- The list omits a number of important behavioral components (e.g., motor function, long-term memory, psychophysical sensitivity), but these are poorly represented in studies of stress effects and, therefore, could not be considered across a wide range of conditions.
- General alertness includes both subjective estimates and physiological measures of arousal which may be tapping different aspects of the stress state.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

7.410 Maintenance of vigilance level by adaptive changes in signal detectability;

7.411 Characteristics of the task that affect vigilance, monitoring, and search;

7.417 Effect of boredom on detection efficiency;

7.803 Effect of anxiety on performance;

10.201 Types of tasks used in measuring the effects of stress, fatigue, and environmental factors on performance;

10.303 Continuous broadband noise: effect on vigilance performance as a function of number of monitored sources;

10.305 Continuous open-field white noise: effect on speed/accuracy tradeoffs in serial response tasks;

10.307 Continuous noise: effect on sampling of signal sources;

10.309 Continuous noise: effect on performance of a letter-transformation task with varying memory load;

10.712 Schedule shift: effect on performance;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.810 Selective sleep deprivation: effect on memory;

10.811 Partial sleep deprivation: effect on vigilance and cognitive performance

10.301 Noise Bursts: Effect on Task Performance

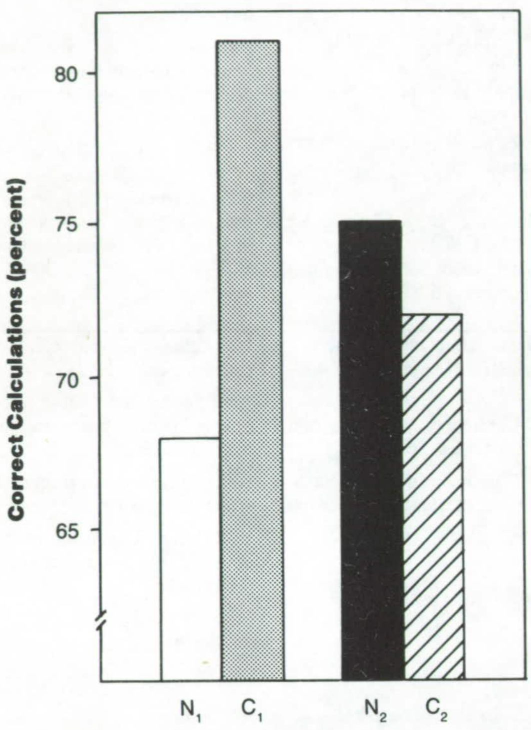

Figure 1. Accuracy of calculations for subjects experiencing a noise burst during the memorization of the first number (N_1), during the calculation period (N_2), or when no noise was presented (Control—C_1, C_2). (Adapted from Ref. 7)

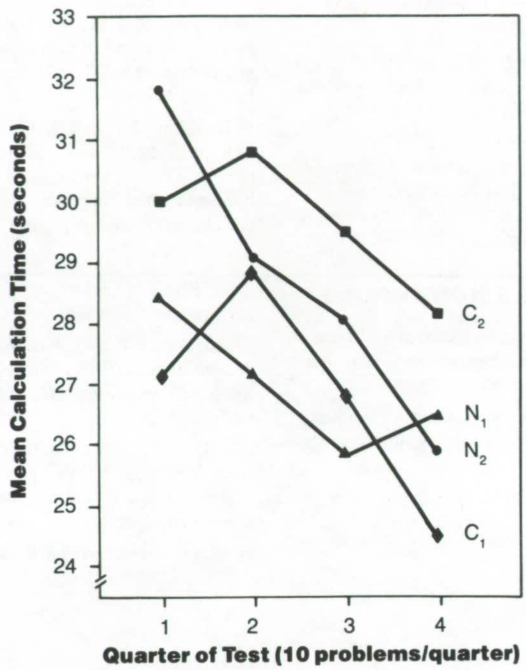

Figure 2. Mean time to perform one calculation as a function of test segment. Abbreviations are as in Fig. 1. (From Ref. 7)

Key Terms

Arousal; autonomic activity; noise; startle reaction; vasodilation

General Description

A brief burst of noise can cause subjects to undergo a startle reaction, characterized by an increase in autonomic nervous system activity [vasodilation, tachycardia (rapid pulse), increased skin conductance, etc.]. Depending on the task, this brief distraction can impair performance or act as an arouser, improving performance in certain ways.

Methods

Test Conditions

- Subject in small cubicle with screen and two loudspeakers for presentation of noise
- 120 subtractions, each consisting of a six-digit number shown on screen for 10 sec, to be memorized, followed by four-digit number (to be mentally subtracted from the first number) which remained on screen until calculation completed; only the integers 1, 2, 3, and 4 used, and "borrowing" always required in three columns
- Subject pressed a bell after writing down the remainder; next calculation began in 15 sec
- Noise conditions: N_1, burst of noise began 4 sec after the six-digit number appeared; N_2, burst of noise began 5 sec after the four-digit number appeared; noise was 1-sec record of rocket firing, mainly low frequencies with peak intensity of 100 dB; no noise presented for 2 identical matched for order control groups (C_1, C_2)
- 40 calculations per day for 3 days in counterbalanced order

Experimental Procedure

- Independent variables: noise, stage of noise presentation
- Dependent variables: accuracy (percentage of calculations correct); speed (mean overall time to calculate problems, averaged for quarter parts of the test [ten problems in each quarter]); results reported only for Day 3 of testing when subjects most accustomed to noise bursts
- Subject's task: mentally subtract a four-digit number from a six-digit number, previously memorized, write down remainder, and signal completion by bell push
- 84 subjects, young naval enlisted men with normal hearing; 21 in each of four groups, balanced for intelligence test scores; some practice

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Experimental Results

- Control group C_1 alone ($p < 0.05$) and combined with C_2 ($p < 0.03$) perform calculations more accurately than subjects (N_1) experiencing a noise burst during memorization (Fig. 1).
- Groups C_1 and N_1 perform with similar speed.
- Noise during calculation did not affect accuracy or speed overall (N_1 versus C_2), although largest reduction in speed during the progress of the test is by N_2 subjects ($p < 0.05$) (Fig. 2).

Variability

Type of statistical analysis not specified. Group C_1 was faster and more accurate than the other three groups, but individual differences in performance are not discussed.

Repeatability/Comparison with Other Studies

Continuous broadband noise increases speed of performance of older men on a checking task (CRef. 10.306). Performance has been impaired briefly following bursts of noise on a visual inspection task (Ref. 6), on serial responding (Ref. 1), and on a pursuit tracking task (Ref. 3).

On forced-choice signal detection tasks, noise bursts presented simultaneously with detection stimuli facilitate performance, but bursts outside the target interval impair performance (Ref. 5).

On a letter transformation task, as the demands on working memory increase with longer sequences of letters, the effect of continuous noise changes from facilitatory (with single letters) to markedly inhibitory (Ref. 2; CRef. 10.309).

Constraints

- Speed was emphasized in feedback in pretask training, so that those in Noise Group 2 (N_2) may have used the regularly recurring noise burst to pace themselves on the unpaced portion of the task; other groups did not have such a signal to use for pacing.

Key References

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Cross References

10.101 Theories of arousal and stress;

10.104 Arousal level: effect on performance;

10.202 Effects of different stressors on performance;

10.302 Continuous broadband noise: effect on task performance;

10.306 Continuous noise: effects on performance for different age groups;

10.309 Continuous noise: effect on performance of a letter-transformation task with varying memory load;

10.805 Five-choice serial response task: effect of different stressors on performance

10.302 Continuous Broadband Noise: Effect on Task Performance

Table 1. Effects of noise on task performance.

Task Type	Improvement	Impairment	Selectivity	Summary	Source
Vigilance task performance	Increases hit rate and/or abolishes vigilance decrement for tasks with single signal source or low signal rate Increases hit rate and/or decreases detection latency for high confidence responses	Decreases hit rate and/or increases vigilance decrement for tasks with multiple signal sources or high signal rate Decreases hit rate and/or increases detection latency for low-confidence responses	Improves hit rate and/or detection latency for certain sources or tasks and at same time impairs hit rate and/or detection latency for other sources or tasks on multisource or dual tasks Speed and error rate may increase, or speed may increase while error rate is unchanged, or error rate may increase while speed is unchanged on self-paced tasks	Impairment is likely only when signals are difficult to detect, signal rate is high, and/or the task situation encourages risky decision behavior In general, noise causes increased sampling of the dominant or more probable aspects of the task	Refs. 1, 4, 5, 14, 18, 19, 22, 23 CRefs. 10.303, 10.304, 10.307, 10.308, 10.310
Serial response task performance	Increases speed; increases number of correct responses	Decreases speed; increases errors; increases gaps (long latency responses) Increases errors and gaps on task begun after noise of 20-30 min duration has ceased	Speed and error rate may increase while error rate is unchanged, or error rate may increase while speed is unchanged May increase number of correct responses and/or abolish vigilance decrement, but increases the number of gaps	Exceedingly diverse patterns of effects have been found	Refs. 2, 8, 11, 17, 24 CRefs. 10.305. 10.306, 10.310
Memory/ cognition task performance	Increases recall for dominant aspects of stimulus Increases recall for sequential information Facilitates delayed recall if present during learning Facilitates performance when demand on working memory is low	Decreases recall for incidental aspects of stimulus; decreases recall for semantic information Impairs performance when demand on working memory is high; impairs immediate recall if present during learning Impairs performance on problem-solving and perceptual classification tasks begun after noise of 20-30 min duration has ceased	Increases accuracy on targeted material and decreases accuracy on incidental aspects in incidental learning tasks Increases recall for sequential information and decreases recall for semantic information when both types of material are in same task	Effect depends on when noise occurs, amount of memory load, type of information, and task type	Refs. 3, 6, 9, 10, 12, 15, 16, 20, 21 CRefs. 10.308, 10.309, 10.310

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Broadband noise; key pressing; memory; monitoring; noise comfort level; serial recall; stereoscopic ranging; stressors; tracking; vigilance; white noise

General Description

Continuous broadband noise at ~100 dB affects performance on vigilance, serial response, and memory (cognitive) tasks. Although noise is usually considered a stressor, it does not always impair performance. Noise improves performance on certain tasks or on parts of a task; it may cause impairment on one aspect of a task and simultaneous improvement on another. Performance on a task after exposure to noise may also be affected. Table 1 lists the types of tasks on which the effects of noise have been studied, describes its positive, negative, and selective effects, summarizes the findings, and gives sources of more information. Table 2 indicates noise effects on specific mental and motor tasks.

Constraints

- Effects vary with type, duration, and complexity of task.
- Noise may interact with other stressors or arousers to alter some of the effects listed here (Ref. 23).
- If subjects are led to believe they can control the noise (even if this is not the case), the effects of noise are reduced (Ref. 7).

Table 2. Some effects of exposure to noise as compared to quiet on human performance and other processes. (From Ref. 13)

Type of Performance	Noise Level (dB)	Noise Duration	Quiet level (dB)	Effect of Noise
Addition problems	50	Continuous	Not given	No difference in number of correct solutions. Considerable increase in energy expenditure under noise as compared to quiet, especially during first few days
Continuous tracking	120	Intermittent and random	" "	No effect
	120	12 × 2 min in 4 hr	" "	Performance improved
	130	3 min at middle and end of 4 hr	" "	Performance improved
Stereoscopic ranging	120	3 min	" "	No effect
Inserting pegs in pegboard	High	Intermittent clicks and complex noise	" "	Initial performance slowed, but overall performance showed no difference
Tracking requiring hand, foot, and eye coordination	115	Continuous	90	Reactions in noise 5.4% slower
Card sorting	115	Continuous	90	No effect
Marksmanship	115	Continuous	90	No effect
Joystick pursuit tracking	115	Continuous	90	No effect
Hand or foot key-pressing	115	Continuous	90	No effect
Key pressing to translate letters to numbers	120	10 min	Not given	Time required initially longer; greater tension in noise
Monitoring clock for erratic hand movements	114	Last 1½ hrs of 2-hr trial	83	Significantly poorer in last ½ hr
Conversation	0-60	Continuous	—	Normal
	60-80	"	—	Raised voice needed
	80-100	"	—	Very difficult
	100-115	"	—	Shouting necessary
	>115	"	—	Impossible
Comfort level in aircraft	0-60	Continuous	—	Quiet and very comfortable
	60-80	"	—	Comfortable
	80-90	"	—	Acceptable
	90-100	"	—	Noisy
	100-115	"	—	Very noisy and disagreeable
	115-125	"	—	Uncomfortable
	>125	"	—	Painful

Key References

1. Broadbent, D. E. (1954). Some effects of noise on visual performance. *Quarterly Journal of Experimental Psychology, 6*, 1-5.

2. Broadbent, D. E. (1957). Effects of noises of high and low frequency on behavior. *Ergonomics, 1*, 21-29.

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Cross References

2.613 Loudness discomfort level;

8.304 Factors affecting the intelligibility of speech in noise;

10.201 Types of tasks used in measuring the effects of stress, fatigue, and environmental factors on performance;

10.303 Continuous broadband noise: effect on vigilance performance as a function of number of monitored sources;

10.304 Continuous noise: effect on a dual vigilance task;

10.305 Continuous open-field white noise: effect on speed/accuracy tradeoffs in serial response tasks;

10.306 Continuous noise: effects on performance for different age groups;

10.307 Continuous noise: effect on sampling of signal sources;

10.308 Continuous noise: effect on incidental learning;

10.309 Continuous noise: effect on performance of a letter-transformation task with varying memory load;

10.310 Continuous broadband noise: performance-related aftereffects of exposure

Notes

10.303 Continuous Broadband Noise: Effect on Vigilance Performance as a Function of Number of Monitored Sources

Key Terms

Broadband noise; monitoring; noise; signal detection; stress; vigilance

General Description

High-intensity (112 dB) broadband noise has no effect on the overall level of signal detection (vigilance level) or on the decline in detection rate over time (vigilance decrement) in a vigilance task when only one signal target source (a clock) is monitored, but significantly impairs detection (at 114 dB) for the last half-hour of a 2-hr task when three sources of signal targets are monitored.

Methods

Test Conditions

Study 1 (Ref. 3)

- Clock hand normally made 0.03 sec, 10-deg jumps; signal target was double jump of 20 deg (0.06 sec); double jumps replaced single jumps 13 times in 26.7 min period; intervals between double jumps: 120, 80, 80, 160, 40, 160, 160, 120, 160, 80, 80, 200 and 160 sec (repeated four times for watch duration of 1.78 hr); quiet, 79 dB SPL, or noise, 112.5 dB SPL; auditory stimuli were all broadband noise
- Two sessions 1 week apart; no information on training given
- Quiet and noise conditions order counterbalanced

Study 2 (Ref. 4)

- Three clocks, each with one revolving hand, set in panel with one response switch below each clock face
- On all three clocks hand normally made 3.6-deg jumps; signal target was double jump of 7.2 deg; double steps occurred randomly at intervals that averaged about one per min for each clock during 2-hr session; 2 hr of quiet or 0.5 hr quiet and 1.5 hr noise
- Two noise levels: quiet: 83 dB SPL; noise: 114 dB SPL; noise broadcast by loudspeaker in subject's room
- Three sessions 1 week apart for three clocks; first was 1 hr training in quiet condition
- Subjects served in quiet and noise conditions; order counterbalanced

Experimental Procedure

- Independent variables: noise level, number of sources monitored
- Dependent variable: percent correct detection rate of signal targets
- Subject's task: press response button to indicate detection of double jump of pointer hand
- 20 (Study 1) and 9 (Study 2) male undergraduate subjects

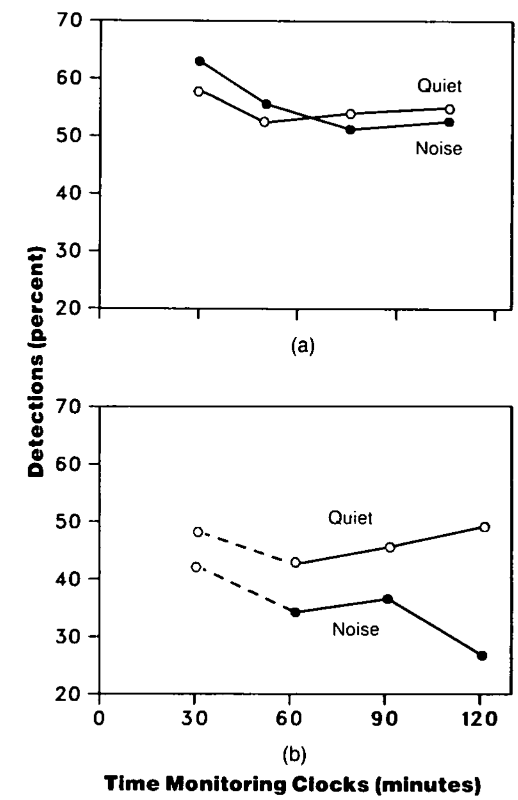

Figure 1. Detection accuracy as a function of time monitoring (a) one clock (Study 1) or (b) three clocks (Study 2) in noise or quiet. In (b), first half of noise condition was in silence. (From *Handbook of perception and human performance*, based on data from Refs. 3 and 4)

Experimental Results

- In one-clock vigilance task, detection rates decrease only slightly with time.
- In one-clock task, noise affects neither the overall vigilance level nor its decrement (Fig. 1).
- In three-clock vigilance task, detection rate decreases only in the last half hour under noise conditions ($p<0.05$) (Fig. 1).
- In three-clock vigilance task, except for the decrement during last 0.5 hr, the detection level is similar under quiet and noise conditions.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Noise has a detrimental effect on performance in multi-source vigilance tasks, including a 20-dial task (Ref. 1). Replication using a three-source task and a task with a high signal rate for a single source (Ref. 2) suggests that number of sources and signal rate may trade off under noise conditions.

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Constraints

- Meaningfulness of noise, noise level, and characteristics of the observers and task alter the effects of noise on vigilance performance.
- Conditions for one- and three-clock tasks differed in several ways, including signal rate, which varied from an average of one each 2 min for the one-clock task to three per min for the three-clock condition. Signal probability does affect vigilance performance.
- Vigilance in the one-clock task may differ from vigilance in more complex tasks, the latter emphasizing the importance of efficient scanning of several displays (i.e., flexibility), not focusing on a single display.

Key References

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2. Broadbent, D. E., & Gregory, M. (1965). The effects of noise and signal rate upon vigilance analyzed by means of decision theory. *Human Factors, 7,* 155-162.

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*4. Jerison, H. J. (1959). Effects of noise on human performance. *Journal of Applied Psychology, 43,* 96-101.

Cross References

7.209 Factors influencing performance in selective listening tasks;

7.314 Factors affecting monitoring performance;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

7.413 Characteristics of the observer that affect vigilance, monitoring, and search;

10.302 Continuous broadband noise: effect on task performance;

Handbook of perception and human performance, Ch. 44, Sect 3.2

10.304 Continuous Noise: Effect on a Dual Vigilance Task

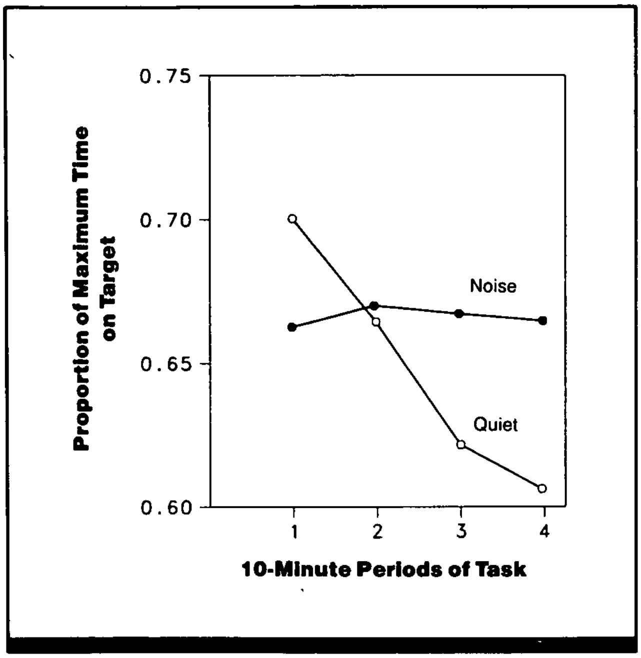

Figure 1. Proportion of maximum time spent pursuing target in tracking task as a function of task segment for quiet and noise conditions. (Adapted from Ref. 2)

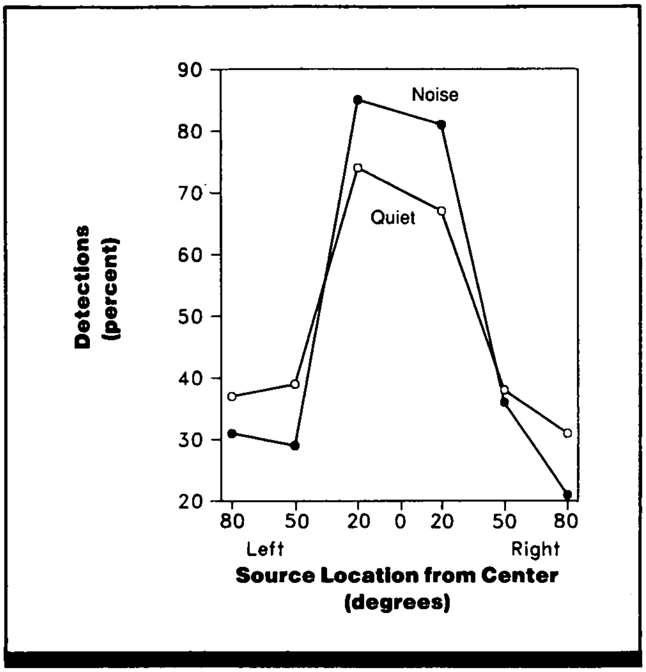

Figure 2. Accuracy on detection task as a function of source location for quiet and noise conditions. (From Ref. 2)

Key Terms

Concurrent tasks; monitoring; noise; signal detection; stress; tracking; vigilance decrement

General Description

Subjects performing a tracking task as a primary task and a signal detection task as a secondary task show less efficiency for the tracking task over time (vigilance decrement). This decrement is abolished by 100-dB broadband background noise. On the secondary task, there is no significant decrement over time and no overall effect on detection level, but noise does increase selectivity so that the detection of central targets is higher and detection of peripheral targets lower than under quiet conditions. Noise has the general effect of focusing attention on the more dominant components of a complex task.

Methods

Test Conditions

- Tracking window centered in the visual field with two lamps at each of three positions (20, 50, and 80 deg from center), all 80 cm from subject
- Primary task: subject moved handle in vertical plane with right hand to pursue target pointer as it was moved from side to side in a window; movement produced by irregularly shaped cam
- Secondary task: subject pressed button corresponding to light that flashed (600 msec; luminance adjusted to satisfy performance criteria of 50% detection); flashes randomized in time and location at average of six per min; panel had response buttons for each lamp under subject's left hand
- Tasks performed twice in both quiet (70 dB) and noise (100 dB), order of presentation counterbalanced; broadband noise, 62.5-4000 Hz, with lower frequency range attenuated in accordance with hearing hazard recommendation (attenuation of 3 dB per octave up to 1000 Hz)
- 40-min session, 1 wk apart; subjects informed as to task priority

Experimental Procedure

- Independent variables: noise, location of lamp in semicircular visual field
- Dependent variables: integrated time on target (TOT) over successive 10-min periods, expressed as proportion of maximum (600 sec), for primary task; percentage of correct detection for each source for secondary task
- Subject's task: keep pointer aligned with moving target pointer, press button corresponding to light that flashed
- 12 subjects, naval personnel, 17-25 yrs, with satisfactory vision and absence of hearing loss >30 dB on both ears or 35 dB on one ear in any frequency band; extensive practice

Experimental Results

- Mean time on target (TOT) for a tracking task (primary task) decreases significantly between first and fourth 10-min periods in the quiet condition ($p < 0.02$) (Fig. 1).
- Mean TOT scores for noise condition show no change over time (Fig. 1), but the difference between mean TOT for noise and quiet conditions increases with time on the tasks.
- Mean percentage of light flashes detected (secondary task) does not differ significantly with time on task for either quiet or noise conditions.

- Noise has no overall effect on detection level.
- Detections are higher for central sources in noise than in quiet ($p < 0.01$) and lower for peripheral sources in noise than in quiet ($p < 0.05$) (Fig. 2).

Variability

Wilcoxon *T* tests were used to determine significance of differences.

Repeatability/Comparison with Other Studies

Noise (100 dB) produces a spatially selective effect on a light-monitoring task, although the lights at the edges are responded to more quickly than those in the middle of the display (Ref. 1). Another study of secondary task performance shows that the form of the focusing effect is related to expectation of events, rather than to intrinsic spatial factors (Ref. 3).

Constraints

- Whether noise (or other stressors) affects the primary, secondary, or neither portion of a dual task, and the kind of effect obtained, depend on many factors, such as the subject's priorities and the task characteristics.
- The combination of noise with other stressors results in complex interactions with respect to performance.

Key References

1. Broadbent, D. E. (1954). Some effects of noise on visual performance. *Quarterly Journal of Experimental Psychology, 6*, 1-5.

*2. Hockey, G. R. J. (1970). Effect of loud noise on attentional selectivity. *Quarterly Journal of Experimental Psychology, 22*, 28-36.

3. Hockey, G. R. J. (1970). Signal probability and spatial location as possible bases for increased selectivity in noise. *Quarterly Journal of Experimental Psychology, 22*, 37-42.

Cross References

7.314 Factors affecting monitoring performance;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

10.104 Arousal level: effect on performance;

10.302 Continuous broadband noise: effect on task performance;

10.303 Continuous broadband noise: effect on vigilance performance as a function of number of monitored sources;

10.805 Five-choice serial response task: effect of different stressors on performance

10.305 Continuous Open-Field White Noise: Effect on Speed/Accuracy Tradeoffs in Serial Response Tasks

Key Terms

Monitoring; noise; serial responding; speed-accuracy tradeoffs; stress; white noise

General Description

On a self-paced five-choice serial response task (CRef. 10.805), 100-dB broadband noise increases the number of errors, without affecting the average rate of responding and without significantly altering the number of slow responses (gaps >1.5 sec between responses). The significant increase in number of errors occurs after only 10 min of exposure to noise.

Methods

Test Conditions

- Five neon light bulbs arranged in a pentagon; each bulb could be turned off by the touch of a stylus
- Bulbs normally unlighted; when one is lighted randomly, subject required to touch corresponding contact
- Task performed in faint incidental noise (quiet) or in continuous open field white noise at 100 dB; order counterbalanced
- Subjects served in both conditions 2 days apart

Experimental Procedure

- Five-choice serial response task
- Independent variable: noise
- Dependent variables: number of correct detections of signal targets, number of errors (wrong contact touched), number of slow responses (gaps >1.5 sec between responses)
- Subject's task: detect lighted bulb, touch corresponding contact to alter display; self-paced
- 12 subjects, enlisted men, 18-30 yr, with normal hearing; extensive practice

Experimental Results

- Noise does not affect number of correct detections.
- Noise significantly increases the number of errors after the first 10 min of task.
- Noise neither increases the number of slow responses (gaps >1.5 sec between responses) nor changes the average rate of responding.

Variability

Significance of differences was determined by the Mann-Whitney *U* test.

Repeatability/Comparison with Other Studies

Same pattern of results was reported for five-choice serial reaction task (Ref. 1). Noise was shown to increase speed on a self-paced task without affecting accuracy (Ref. 2). Noise was shown to increase errors, gaps, and speed in five-choice serial reaction task (Ref. 3).

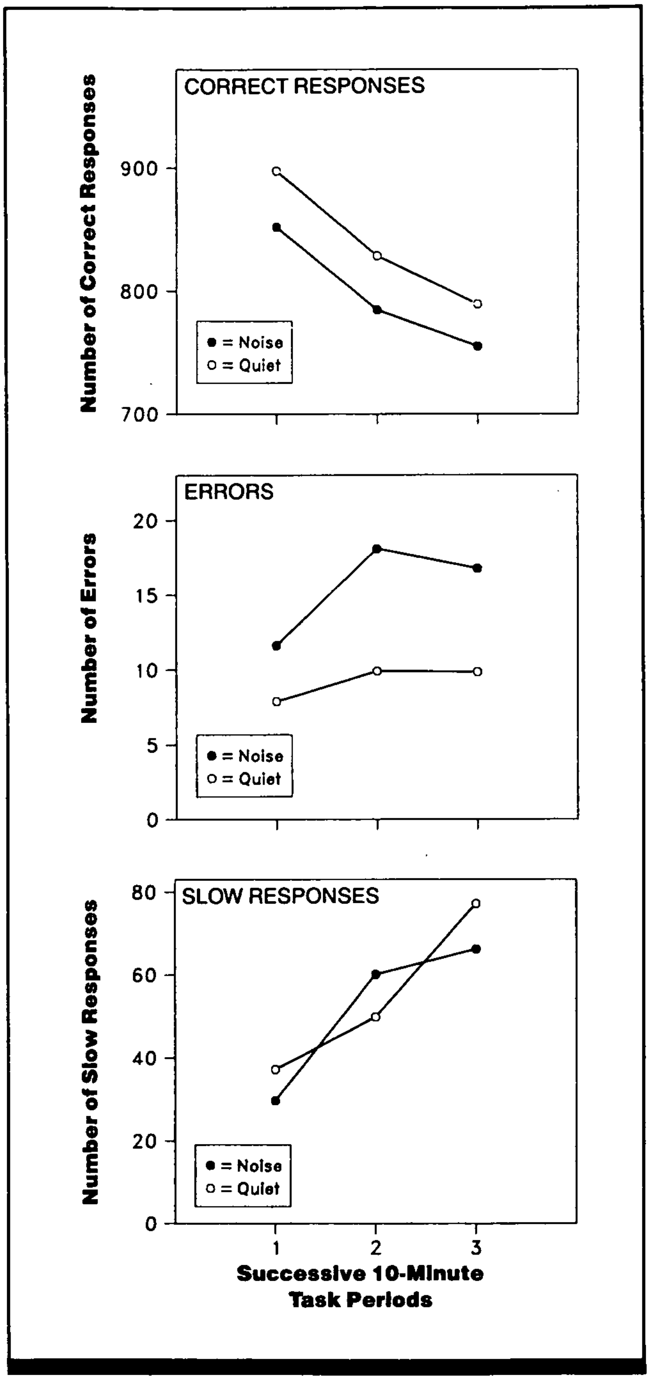

Figure 1. Number of correct responses, errors, and responses >1.5 sec as a function of task segment for quiet and noise conditions. (From Ref. 4)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Broadbent, D. E. (1957). Effects of noises of high and low frequency on behaviour. *Ergonomics, 1*, 21-29.

2. Davies, A. D. M., & Davies, D. R. (1975). The effects of noise and time of day upon age differences in performance at two checking tasks. *Ergonomics, 18*, 321-336.

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Cross References

10.310 Continuous broadband noise: performance-related aftereffects of exposure;

10.805 Five-choice serial response task: effect of different stressors on performance;

Handbook of perception and human performance, Ch. 44, Sect. 3.2

10.306 Continuous Noise: Effect on Performance for Different Age Groups

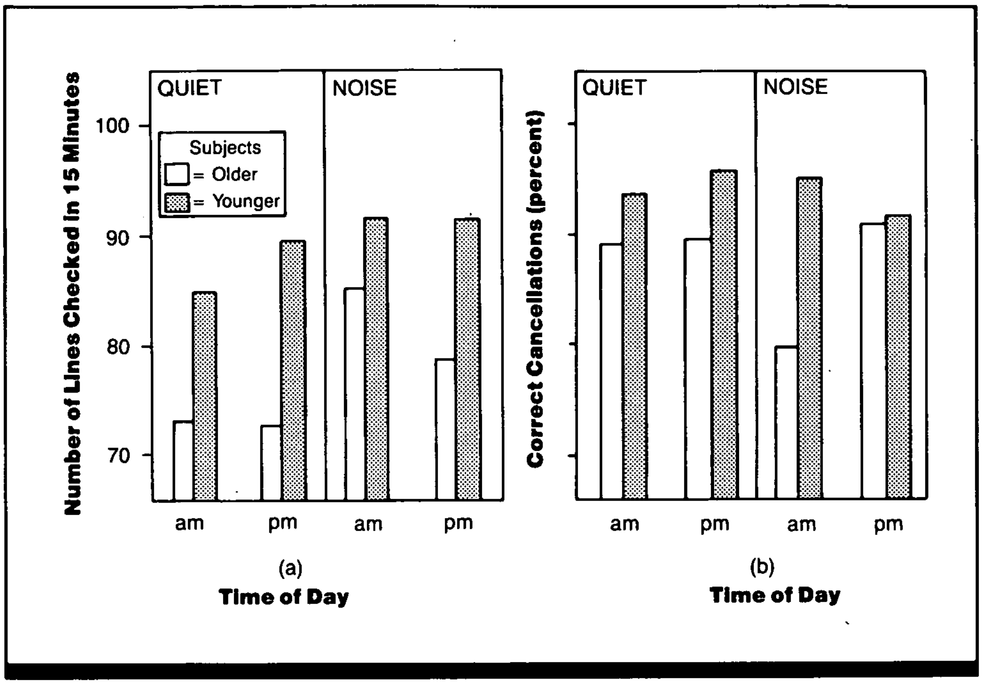

Figure 1. (a) Speed and (b) accuracy of letter cancellation in noise and quiet for younger subjects and older subjects tested at different times of the day. (From Ref. 1)

Key Terms

Proofreading task; self-paced task; vigilance

General Description

On a self-paced cancellation task, subjects cancel a target letter while checking or "proofreading" prose. Older subjects work more slowly and less accurately than younger subjects. The addition of intense, continuous broadband noise increases the speed of performance of older subjects, but does not alter their accuracy. Noise does not significantly affect performance of younger subjects.

Methods

Test Conditions

- English prose typed on foolscap paper; an average of 62 letters per line, 35 lines per page
- In 15 min, subject canceled (with pen) all letter "e's" (signal target, probability of 0.115) in noise (95 dB) or quiet (70 dB) provided by broadband noise, 40-32,000 Hz
- Subject listened to 1 min of expected noise level just prior to test
- Sessions divided into morning and afternoon

Experimental Procedure

- Independent variables: age of subject, noise, time of day
- Dependent variables: speed, accuracy
- Subject's task: cancel all letter "e's"
- 40 older (65-72 yr) and 40 younger (18-31 yrs) male subjects, with 5 min practice (noise level not specified); 10 subjects of each age group per condition; groups matched for temperament, sociability (Heron Scale), and vocabulary level (Mill Hill Vocabulary Score)

Experimental Results

- Younger subjects check significantly more lines than older subjects ($p < 0.01$).
- Older subjects check more lines in noise than in quiet ($p < 0.05$) (Fig. 1a).
- Neither the time of day nor the interaction of noise by time of day affect speed of performance.
- Older subjects are less accurate than younger subjects at both times of day ($p < 0.001$).
- In noise, younger subjects are slightly more accurate in the morning, and older subjects are more accurate in the afternoon ($p < 0.05$). The two age groups are almost equally accurate in noise in the afternoon (Fig. 1b).

Variability

Significance was determined by analysis of variance.

Repeatability/Comparison with Other Studies

When using a *paced* continuous performance test with the same subjects, this pattern of results was not obtained, and noise seemed to increase number of slow responses for older subjects (Ref. 1).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- The same subjects did not participate in quiet and noise conditions, and most vigilance tasks show wide individual differences.
- Only males were tested.
- A task of longer duration might have shown a cumulative effect of noise for younger subjects as well (Ref. 2).

Key References

*1. Davies, A. D. M., & Davies, D. R. (1975). The effects of noise and time of day upon age differences in performance at two checking tasks. *Ergonomics, 18*, 321-336.

2. Hartley, L. R. (1973). Effect of noise of prior performance on serial reaction. *Journal of Experimental Psychology, 101*, 255-261.

Cross References

7.314 Factors affecting monitoring performance;

7.411 Characteristics of the task that affect vigilance, monitoring, and search;

7.413 Characteristics of the observer that affect vigilance, monitoring, and search;

10.302 Continuous broadband noise: effect on task performance

10.307 Continuous Noise: Effect on Sampling of Signal Sources

Key Terms

Monitoring; noise; signal detection; stress; vigilance

General Description

In multisource monitoring, an operator must continuously sample (check) the states of several sources of information for signals or faults in functioning. When subjects must actively sample each of three sources to detect a fault, the addition of 100-dB broadband noise alters the selection pattern only when the rate of sampling is limited by pacing and the probability of a fault at one source is considerably higher than the probabilities of faults at the other sources. Noise causes an increased tendency to sample dominant or probable sources of information when time limits impose some selectivity.

Methods

Test Conditions

- Three light sources spaced 76.2 cm apart in triangle, normally off; fault in source indicated by dull red flash upon sampling (intensity adjusted to produce 50% of immediate corrections); viewing distance: 1.5 m
- Control panel with sampling button to check state of source for 50 msec and fault correction buttons for each light source
- One fault in circuit at any one time; fault held in channel until corrected; 5 faults per min, in 6:3:1 ratio among sources, with distribution to actual locations balanced across observers
- For paced condition, subjects took sample every 2 sec when green light at center of display produced dull flash; for unpaced condition, subjects took samples at "manageable" rate
- 32-min task performed in quiet (70 dB SPL) or in noise (100 dB SPL); 62.5-4000 Hz broadband noise

Experimental Procedure

- Independent variables: paced or unpaced, noise
- Dependent variables: degree of selectivity, defined as percentage of sampling responses made on the high-probability source in each 4-min period; detection pattern, consisting of faults corrected after one observation (hits), faults corrected after subsequent independent observation of the source (misses), and faults corrected after two successive observations of the same source (unsure hits)
- Subject's task: check the state of three machines by pressing sampling button and, if a fault is detected, correct it as quickly as possible
- 24 subjects enlisted men from Royal Navy (18-24 yr), with normal vision and hearing; some practice; half in paced condition, half in unpaced condition

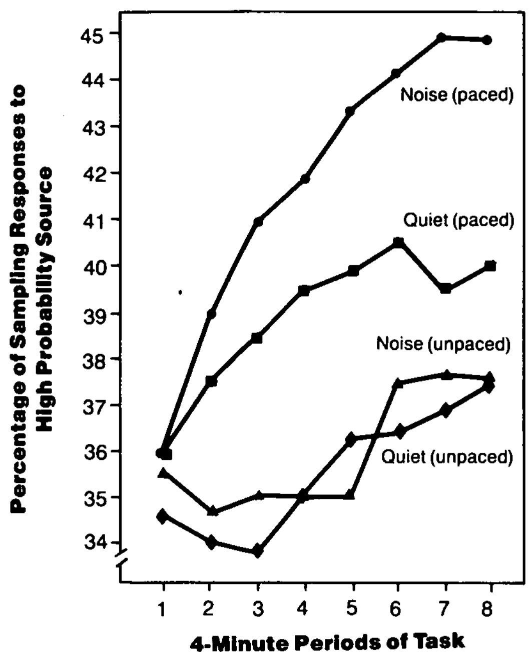

Figure 1. Selectivity as a function of task segment for subjects in paced or unpaced conditions, with or without noise. (Data from Ref. 3)

Experimental Results

- Degree of selectivity is significantly affected by noise, pacing, and period of task ($p < 0.01$) (Fig. 1).
- Sampling rate increases over time in both noise and quiet for the unpaced condition ($p < 0.01$).
- In the paced condition, the number of hits (immediate corrections of a fault) decreases with time on the task (vigilance decrement) in both quiet and noise conditions.
- In the paced condition, noise increases misses ($p < 0.05$) (faults corrected only after subsequent independent observation of the source) but does not change unsure hits (correction of a fault after two consecutive samples of same source), while the reverse pattern is observed in quiet.

Variability

Significance of differences was determined by analysis of variance and the Wilcoxon *T* test.

Repeatability/Comparison with Other Studies

The effect of pacing and high-fault probability on selectivity of sampling holds in a quiet condition (Ref. 1). Noise increases selectivity for central versus peripheral lights on the secondary task of a dual task (Ref. 2). Loss of sleep reduces selectivity, particularly as time increases (Ref. 3).

Constraints

- The effects of noise interact with the effects of other stressors, so that the same patterns are not always found, depending on other conditions.

Key References

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2. Hockey, G. R. J. (1970). Effect of loud noise on attentional selectivity. *Quarterly Journal of Experimental Psychology, 22*, 28-36.

*3. Hockey, G. R. J. (1973). Changes in information selection patterns in multisource monitoring as a function of induced arousal shifts. *Journal of Experimental Psychology, 101*, 35-42.

Cross References

7.314 Factors affecting monitoring performance;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

10.301 Noise bursts: effect on task performance;

10.304 Continuous noise: effect on a dual vigilance task

10.308 Continuous Noise: Effect on Incidental Learning

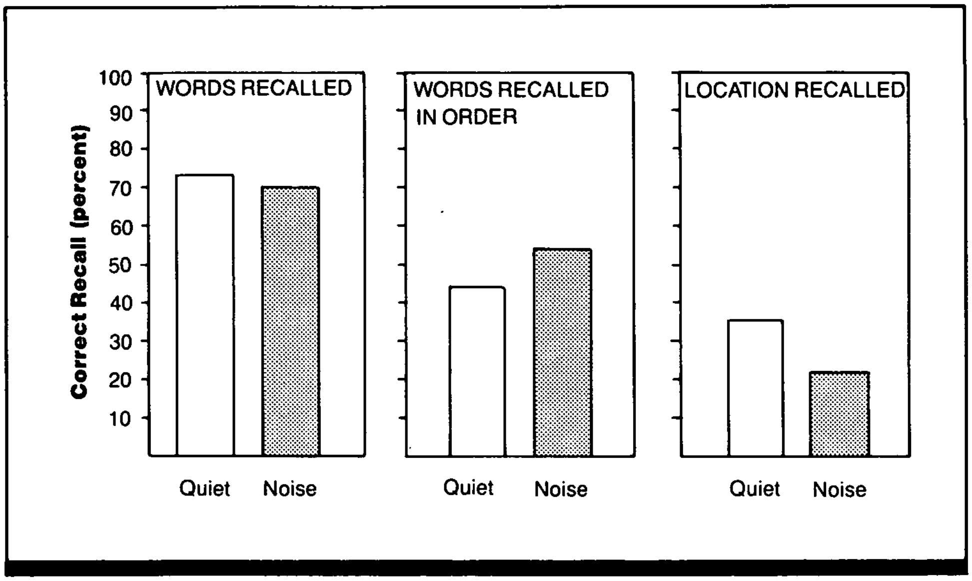

Figure 1. Mean percentage of relevant cues (words, order of words) and irrelevant cues (location) recalled in noise or silence. (Adapted from Ref. 3)

Key Terms

Incidental learning; memory; stress; word recall

General Description

With arousal from loud broadband background noise, subjects attend more to high-priority sources of information (those known to be relevant) and are more likely to disregard sources of irrelevant information. Knowing they would be asked for ordered recall of a list of words, subjects perform marginally better under noise than under quiet conditions for the relevant cue (order) but significantly worse on the irrelevant cue of location, which was not defined in advance as part of the memory task.

Applications

Design of the work environment.

Methods

Test Conditions

- Eight slides, each containing a common two syllable adjective in one corner, presented 1 per 2 sec in noise (80 dB) or quiet (55 dB); two slides for each of the four corners; no two successive slides presented words in the same corner

Experimental Procedure

- Independent variables: noise, presentation location
- Dependent variables: percentage of words recalled, percentage of words recalled in correct order, percentage of locations correctly assigned to recalled words
- Subject's task: after all slides presented, recall words in order in writing and place cross in corner where word appeared on slide
- 36 subjects in quiet, 32 subjects in noise condition

Experimental Results

- Higher percentage of words recalled in correct order for the noise condition (54.12) than for the quiet condition (43.75), although the effect is not established (is not statistically significant).
- Regardless of order of words recalled, a higher percentage of words is recalled in quiet (73.12) than in noise (69.0).
- For the incidental task—recalling the location of the words as a function of the percentage of words recalled—a significantly higher percentage of locations is recalled in the quiet condition (48.5% of 73.12% = 35.46%) than in the noise condition (32% of 69% = 22%) ($p < 0.05$) (Fig. 1).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Reference 2 reports the same pattern of results. In learning nonsense syllables, verbal recall is unaffected by 95-dB noise, while the content of pictures presented alongside the syllables is impaired (Ref. 1).

Constraints

- Word order and spatial location of words were not counterbalanced in different conditions.
- Individual differences were not controlled.

Key References

1. Cohen, S., & Lezak, A. (1977). Noise and inattentiveness to social cues. *Environment and Behaviour*, *9*, 559-572.

2. Davies, D.R., & Jones, D.M. (1975). The effects of noise and incentives upon attention in short-term memory. *British Journal of Psychology*, *66*, 61-68.

*3. Hockey, G.R.J., & Hamilton, P. (1970). Arousal and information selection in short-term memory. *Nature*, *226*, 866-867.

Cross References

10.302 Continuous broadband noise: effect on task performance;

10.304 Continuous noise: effect on a dual vigilance task

10.309 Continuous Noise: Effect on Performance of a Letter-Transformation Task with Varying Memory Load

Key Terms

Short-term memory

General Description

In a letter transformation task, subjects make a forward transition of variable length for a given letter (e.g., B + 1 = C) or group of letters (e.g., FBRJ + 4 = JFVN) with output permitted only after an entire group has been transformed. For a small memory load (0 or 1 item stored), noise (85 dB) is facilitatory (the transformations required less time than in the quiet condition). But as the memory load is increased to three items, the effect of noise is detrimental to performance.

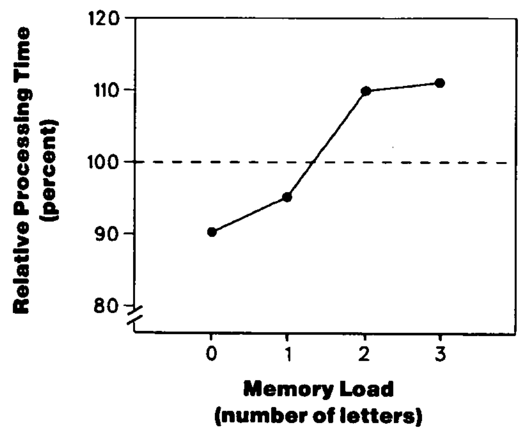

Figure 1. Relative processing time in noise condition as a function of the number of letters presented. The dotted line represents performance in quiet. (From Ref. 2, based on data of Ref. 3)

Methods

Test Conditions

- 1, 2, 3, or 4 letters, arranged in columns on sheets of paper; one letter group size per column per sheet of paper
- In noise (85 dB) or quiet (50 dB), subject worked down these columns performing the required transformation: advance one to four letters to the single letter or to each letter in the group, e.g., B + 4 = F, BS + 1 = CT, JMF + 2 = LOH etc.
- Work on each sheet was terminated before all the items had been transformed
- Memory load of 1, 2, 3, or 4 letters in stimulus, representing loads of 0, 1, 2, or 3 to store; number of transitions: 1, 2, 3, or 4 letters
- Each subject performed the 16 tasks (4 memory load x 4 transition lengths) in counterbalanced design, either in noise or in quiet

Experimental Procedure

- Independent variables: noise level, memory load, number of transitions
- Dependent variable: mean transformation time per letter output for each sheet (memory load and transformation types paired) expressed as percentage of noise condition transformation times to quiet condition times transformation for same pair of letter groups
- Subject's task: transform single letters or each letter in group and hold in memory until all letters completed, then write answer
- 12 subjects in noise condition, 12 subjects in quiet condition

Experimental Results

- Time per letter transformation increases as memory load (number of letters) increases and as transformation length increases.
- In the low memory load condition, time per letter transformation is slightly less in noise than in quiet; the reverse is true for the high memory load condition.
- Over the range of storage loads, the rate of change of performance efficiency is higher in noise than in quiet, ($p < 0.002$)

Variability

Significance was determined by the Mann-Whitney U test.

Repeatability/Comparison with Other Studies

The data comply in form to the Yerkes-Dodson law (CRef. 10.104) in that performance on difficult tasks tends to suffer under stress, while performance on easy tasks tends to benefit. However, the deterioration may stem from a change in the relationship between storage and processing power (Ref. 3). Noise slows the rate of work on an arithmetic task in which a two-digit number must be committed to memory before the addend is presented (Ref. 1).

Constraints

- Errors were not mentioned although the presence of noise sometimes alters speed/accuracy trade-offs.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Broadbent, D. E. (1958). *Perception and communication*. London: Pergamon Press.

2. Eysenck, M. W. (1982). *Attention and arousal: Cognition and performance*. Berlin: Springer-Verlag.

*3. Hamilton, P., Hockey, G. R. J., & Rejman, M. (1977). The place of the concept of activation in human information processing theory: An integrative approach (pp. 463-486). In S. Domic (Ed.), *Attention and performance VI* (pp. 463-486). New York: Academic.

Cross References

7.314 Factors affecting monitoring performance;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

10.104 Arousal level: effect of performance;

10.201 Types of tasks used in measuring the effects of stress, fatigue, and environmental factors on performance;

10.202 Effects of different stressors on performance;

10.302 Continuous broadband noise: effect on task performance;

10.305 Continuous open-field white noise: effect on speed/accuracy tradeoffs in serial responses tasks;

10.704 Time of day: effect on memory;

10.707 Circadian variation in work efficiency;

10.805 Five-choice serial response task: effect of different stressors on performance;

Handbook of Perception and Human Performance, Ch. 44, Sect. 3.2

10.310 Continuous Broadband Noise: Performance-Related Aftereffects of Exposure

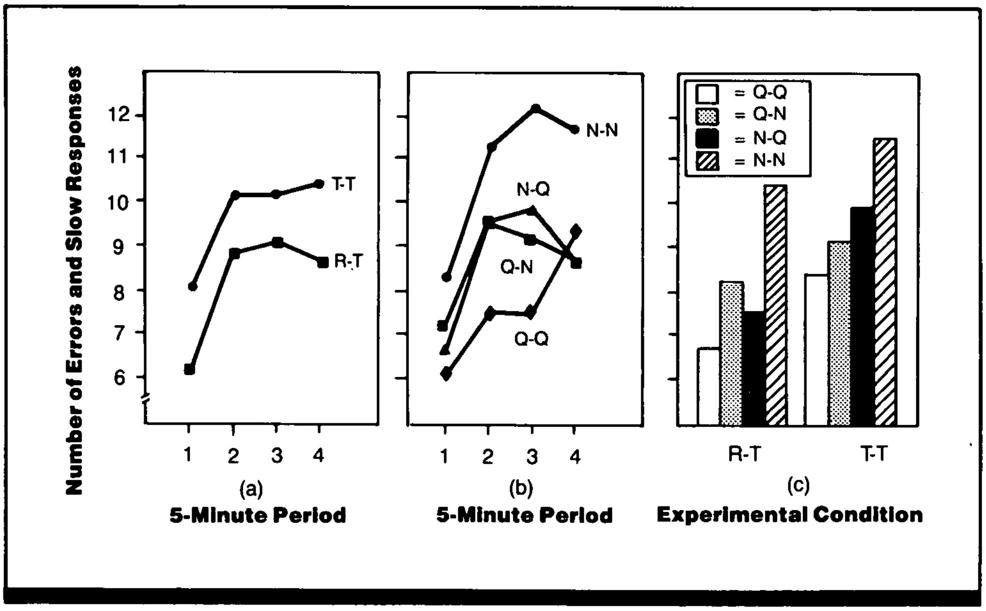

Figure 1. The effect on performance of (a) length of task over the final 20 minutes of the task, (b) noise conditions, and (c) interaction of the length of task and noise conditions. R – T = subject read for the first 20-minute segment of the session and performed the task during the second and final 20-minute segment, T – T = subject performed the task during both 20-minute periods; N – N = noise was presented during both 20-minute segments, N – Q = noise was presented only during the first 20 minutes, Q – N = noise was presented only during the final 20 minutes, Q – Q = both 20-minute periods were run under quiet conditions. (From Ref. 3)

Key Terms

Noise aftereffects; serial responding; stress

General Description

The presence of continuous high-intensity noise affects performance on various tasks, and these effects are generally noted toward the end of a lengthy task. To determine the interaction of noise exposure with prolonged work, observers are exposed to a half (20 min) or whole session (40 min) of high-intensity broadband noise and to a half or whole session of a five-choice serial response task (CRef. 10.805). Equal durations of noise and task impair performance about equally, and a whole session of noise causes twice as much impairment as a half session. Noise impairment is similar when the task is performed for a whole or half session. Noise has a cumulative adverse effect on performance; i.e., the amount of impairment increases as the exposure to noise increases. Impairment caused by noise exposure and by task duration is additive.

Methods

Test Conditions

- Five neon light bulbs arranged to form a pentagon in front of observers; five correspondingly arranged circuits which can be closed by the touch of a stylus
- Bulbs normally unlighted; when one is lighted randomly, observer required to touch corresponding contact
- Task: self-paced, as touching any contact changed display
- Task performed for half (20 min) or whole session (40 min) in quiet (70 dB) or noise (100 dB); broadband noise, 62.5-4,000 Hz; abbreviations: 4 noise conditions: N-N: 40 min noise; Q-N: 20 min quiet, 20 min noise; N-Q: 20 min noise, 20 min quiet; Q-Q: 40 min quiet; 2 task conditions: R-T: 20 min reading, 20 min five-choice serial response task; T-T: 40 min five-choice serial response task
- During a session, each observer's best score on any 5-min block of previous session was presented in a group chart near him and pointed out before session began; in T-T condition, observer was informed halfway through session of his best score for a 5-min block in the first 20 min of task
- When observer was reading for R-T condition, experimenter sat in room
- Each observer served in all eight conditions; order of presentation was randomized across observers, but spacing of eight sessions was not described

Experimental Procedure

- Independent variables: noise level, session length, length of task
- Dependent variables: correct detection of signal target, number of errors (wrong contact touched), number of slow responses (gaps >1.5 sec between responses); all values averaged for each 5-min block of last 20 min of session
- Observer's task: detect lighted bulb, touch corresponding contact to alter display
- 13 subjects, naval enlisted men, 18-30 years, with normal hearing

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Analysis of variance on errors and gaps (slow responses) indicate that these two response measures are levels of a single factor; therefore, further analyses for noise, prior work, and their interaction are based on pooled error and gap scores.
- Noise does not affect detection accuracy.
- Performance, defined as number of errors and gaps, is worse in the T-T than in the R-T condition, and performance decreases over the course of the task; that is, prior work interacts with time on the task (left panel, Fig. 1).
- The adverse effect of T-T and R-T is similar in each noise condition, for noise does not interact with prior work condition (right panel, Fig. 1).
- As compared to Q-Q, both N-Q and N-N cause impairment ($p < 0.01$), indicating a main adverse aftereffect of noise (middle panel, Fig. 1).
- Amount of impairment caused by noise increases with exposure to noise, as performance for N-N is significantly worse than N-Q or Q-N ($p < 0.05$) (middle panel, Fig. 1).

Variability

Interactions between factors and observers were used as error terms throughout the analysis of variance.

Repeatability/Comparison with Other Studies

References 1 and 2 report similar effects of noise on subsequent performance on problem-solving tasks and perceptual classification. Errors only (and not gaps) increase as a result of noise on a five-choice serial response task (Ref. 4).

Constraints

- Knowledge of results is known to alter effect of noise on performance of vigilance tasks.
- Both aftereffects and direct effects of noise are attenuated by allowing subjects to believe that they have control over the noise (Ref. 1).

Key References

1. Cohen, S., & Weinstein, N. D. (1981). Non-auditory effects of noise on behaviour and health. *Journal of Social Issues, 37,* 36-70.

2. Glass, C.D., & Singer, J. E. (1972). *Urban stress.* New York: Academic Press.

*3. Hartley, L. R. (1973). Effect of noise or prior performance on serial reaction. *Journal of Experimental Psychology, 101,* 255-261.

4. Wilkinson, R.T. (1963). Interaction of noise with knowledge of results and sleep deprivation. *Journal of Experimental Psychology, 66,* 332-337.

Cross References

7.314 Factors affecting monitoring performance;

7.406 Characteristics of the signal that affect vigilance, monitoring, and search;

10.103 Classification of factors influencing the stress state;

10.202 Effects of different stressors on performance;

10.302 Continuous broadband noise: effect on task performance;

10.305 Continuous open-field white noise: effect on speed/accuracy tradeoffs in serial response tasks;

10.805 Five-choice serial response task: effect of different stressors on performance

10.311 Factors Affecting the Temporary Threshold Shift

Factor	Manipulation	Effect	Source
Frequency	Vary center frequencies of narrow-band noise	Maximum TTS occurs at a signal frequency ½ octave above noise center frequency. Low-frequency (<2000 Hz) noises injure the cochlea and produce a high-frequency hearing loss	Ref. 3 CRef. 10.313
Intensity	Alter sound pressure level of noise, pulsed tones, gunshots, or clicks	TTS grows linearly with sound pressure level	Refs. 2, 4 CRef. 10.312
Exposure duration	Vary duration of octave band noise	TTS grows linearly with exposure duration (up to 4-12 hrs of exposure)	Refs. 2, 3, 4 CRefs. 2.311, 10.313, 10.315
Number and spacing of impulses	For impulse noise (such as clicks), vary the number of impulses or the time between successive impulses	Between 1000 and 3000 Hz, TTS grows linearly with number of impulses. For intervals between impulses of <1 sec, TTS does not increase. If the interval increases sufficiently, TTS decreases	Ref. 2
Time since last exposure	Threshold measured at various intervals after exposure to noise	Recovery begins 5 sec after exposure, increases linearly (threshold decreases) as a function of time, and depends on the amount of original TTS. Permanent hearing losses are reported	Refs. 1, 2 CRef. 10.312

Key Terms

Hearing loss; noise exposure; noise threshold; temporal threshold shift (TTS)

General Description

Exposure to a sound of sufficient intensity and duration can temporarily raise thresholds for (reduce sensitivity to) nearby frequencies. Both the degree and duration of the threshold shift increase as length of exposure and level of intensity increase. Four to 12 hrs of exposure produces an asymptotic threshold shift. Recovery from temporary threshold shift (TTS) begins ~5 sec after stimulus termination and is a linear function of time. Extreme or repeated TTS may result in permanent hearing loss.

Applications

Keeping noise exposure at low levels to prevent TTS and noise-induced permanent hearing losses.

Constraints

- Does not apply to exposure to noise of individuals with existing hearing impairment. Additive effects to hearing loss are not known.
- Average data are described in the table. Individual effects are not predictable due to large individual differences in effects of exposure.

Key References

1. Davis, H., Morgan, C. T., Hawkins, J. E., Galambos, R., & Smith, F. (1943). Temporary deafness following exposure to loud tones and noise (Contract OEM-CMR-194). Boston, MA; Harvard Medical School, Committee of Medical Research, Office of Scientific Research and Development.

2. Kryter, K. D. (1970). *The effects of noise on man*. New York: Academic Press.

3. Mills, J. H., Gilbert, R. M., & Adkins, W. Y. (1979). Temporary thresholds shifts in humans exposed to octave bands of noise for 16 to 24 hours. *Journal of the Acoustical Society of America, 65*, 1238-1248.

4. Ward, W. D., Glorig, A., & Sklar, D. L. (1958). Dependence of the temporary threshold shift at 4KC on intensity and time. *Journal of the Acoustical Society of America, 30*, 944-954.

Cross References

2.613 Loudness discomfort level;

10.312 Temporary threshold shift and recovery time: effect of noise intensity;

10.313 Temporary threshold shift: effect of noise spectrum;

10.314 Noise-induced hearing loss;

10.315 Factors affecting noise-induced permanent threshold shift;

10.316 Prediction and prevention of hearing loss

Notes

10.312 Temporary Threshold Shift and Recovery Time: Effect of Noise Intensity

Key Terms

Hearing loss; noise exposure; temporary threshold shift (TTS)

General Description

Exposure to loud or long-duration noise can produce a temporary deafness known as temporary threshold shift (TTS). Prolonged or repeated TTS is believed to cause permanent hearing loss, or threshold shift. Several studies agree that the degree of TTS increases linearly with sound pressure level (SPL) of the inducing stimulus, whether the sound is white noise, pulsed tones, gunshots, or clicks. Recovery form TTS is a linear function of $\log_{10}$ time following exposure. The degree of recovery depends on the degree of TTS (which, in turn, depends on intensity and duration of exposure).

Methods

Test Conditions

- Subject exposed to sound of specified duration and intensity; thresholds measured before and after exposure (Table 1)
- Recovery from TTS measured by standard audiometry at intervals after exposure

Experimental Procedure

- Independent variables: sound intensity, time since exposure
- Dependent variable: degree of TTS, defined as the difference in thresholds before and after exposure

Experimental Results

- TTS grows steadily with SPL, basically fitting a function of 20 $\log_{10}$ SPL (Fig. 1).
- Recovery from TTS increases with time since exposure, fitting a function of 10 $\log_{10}$ time (Fig. 2).
- The degree of recovery depends on the degree of TTS.

Constraints

- An individual's TTS for a given exposure cannot be predicted, even if the mean TTS for that exposure is predictable.

Key References

1. Allen, C. H., Jackson, F. J., Kryter, K. D., & Weaver, H. R. (1965). Temporary hearing threshold shift produced by high-level tone bursts. In *Proceedings of the Fifth International Congress on Acoustics*. Liege, Belguim: International Commission on Acoustics.

2. Cohen, A. (1961). *Temporary hearing losses for protected and unprotected ears as a function of exposure time to continuous and impulse noise* (Tech. Rep. EP-151). Natick, MA: U.S. Army Quartermaster Research & Engineering Center, Environmental Protection Research Division. (DTIC No. AD262722)

3. Davis, H., Morgan, C. T., Hawkins, J. E., Galambos, R., & Smith, F. (1943). *Temporary deafness following exposure to loud tones and noise*. (Contract OEM CMR-194). Boston, MA: Committee on Medical Research, Harvard Medical School, Office of Scientific Research and Development.

4. Glorig, A., Ward, W. D., & Nixon, J. (1962). Damage risk criteria and noise-induced hearing loss. In *The control of noise: National physical laboratory symposium number 12* (pp. 263-283). London: Her Majesty's Stationery Office.

5. Harris, J. D. (1967). Relations among aftereffects of acoustic stimulation. *Journal of the Acoustical Society of America, 43*, 1306-1324.

6. Hecker, M. H. L., & Kryter, K. D. (1964). *A study of auditory fatigue caused by high intensity acoustic transients* (Rep. No. 1158). Washington, DC: U.S. Army Medical Research and Development Command, Office of the Surgeon General. (DTIC No. AD450707)

7. Kryter, K. D., & Garinther, G. (1966). Auditory effects of acoustic impulses from firearms. *Acta Oto- Laryngologica, Suppl.211*.

*8. Kryter, K. D. (1970). *The effects of noise on man*. New York: Academic Press.

9. Lewis [personal communication to Kryter (Ref. 8)].

10. Miller, J. D. (1958). Temporary threshold shift and masking for noise of uniform level. *Journal of the Acoustical Society of America, 30*, 517-522.

11. Miller, J. D. (1958). Temporary hearing loss at 4000 cps as a function of a three-minute exposure to a noise of uniform spectrum level. *Laryngoscope, 68*, 660-671.

Table 1. Stimuli and procedures used in each study.

Reference	Stimuli
1	Pulsed tone, 95-110 db
2	White noise mask; after 1-18 min exposure to continuous and impulse, 250-8000 cps test frequency
3	4-8 kHz, 4-kHz tone; 2-min duration; 110-130 db SPL; 2-4 kHz, 2-kHz tone, 2-min duration; 95-120 db SPL
4	1.2-2.4-kHz noise; 480-msec duration; 4 kHz test frequency
5	Impulse and tone at 4 kHz; 3/4-8 min after exposure
6	2, 4 kHz, 100 impulses; 155-170 dB
7	1-, 2-, 3-, 4-kHz tone and gun 100 rounds; 155-170 dB
8	Theoretical (dashed) lines in figures
9	Pulsed tones 10-1000 min after exposure
10	4.6 kHz white noise, 12-min exposure; 95-110 dB
11	4 kHz white noise, 5-min exposure (run 2 min); 110-125 dB
12	Gun; 8-1000 min after exposure
13	4-kHz test frequency; 2-4-kHz noise; 55-min duration; 80-95 dB
14	Gun, 4 kHz; 1-10 min after exposure
15	20-min white noise; 100-110 dB; 5-110 min after exposure
16	1400-2800-Hz noise band; white noise; 1-min duration; 105-125 dB; 3/4-8 min after exposure
17	1, 4 kHz test; 75-9600 cps continuous at 106 dB SPL
18	4 kHz test; 1200-2400 Hz band noise for 47 min; 90-105 dB SPL
19	4-kHz tone; clicks; 75-min exposure; 130-145 dB

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

12. Murray, N. E., & Reid, G. (1946). Temporary deafness due to gunfire. *Journal of Laryngology and Octology*, *61*, 95-130.

13. Shoji, H., Yamamoto, T., & Takagi, K. (1966). Studies on TTS due to exposure to octave-band noise. *Journal of the Acoustical Society of Japan*, *22*, 340-349.

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15. Speith, W., & Trittipoe, W. J. (1958). Intensity and duration of noise exposure and temporary shifts. *Journal of the Acoustical Society of America*, *30*, 710-713.

16. Ward, W. D. (1966). Temporary threshold shifts in males and females. *Journal of the Acoustical Society of America*, *40*, 478-785.

17. Ward, W. D., Glorig, A., & Sklar, D. L. (1958). Dependence of temporary threshold shift at 4 kc on intensity and time. *Journal of the Acoustical Society of America*, *30*, 944-954.

18. Ward, W. D., Glorig, A., & Sklar, D. L. (1959). Temporary threshold shift from octave-band noise: Applications to damage—risk criteria. *Journal of the Acoustical Society of America*, *31*, 522-528.

19. Ward, W. D., Selters, W., & Glorig, A. (1961). Exploratory studies in temporary threshold shift from impulses. *Journal of the Acoustical Society of America*, *33*, 781-793.

Cross References

2.301 Factors affecting auditory sensitivity in quiet;

10.311 Factors affecting the temporary threshold shift;

10.313 Temporary threshold shift: effect of noise spectrum;

10.314 Noise-induced hearing loss

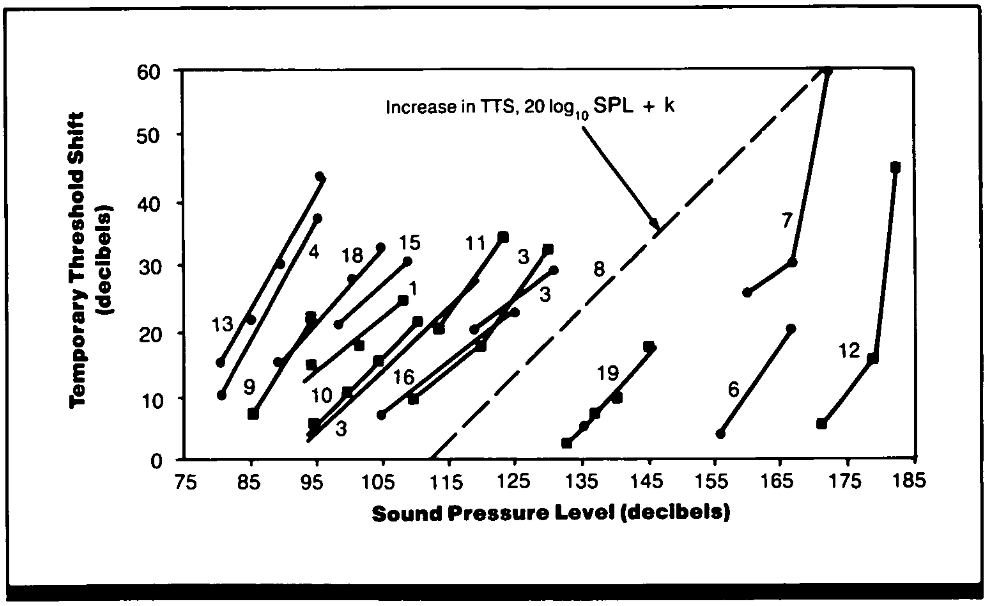

Figure 1. Increase in temporary threshold shift as a function of sound intensity. Reference numbers on curves indicate sources of data points; see Table 1 for summary of test conditions. (From Ref. 8)

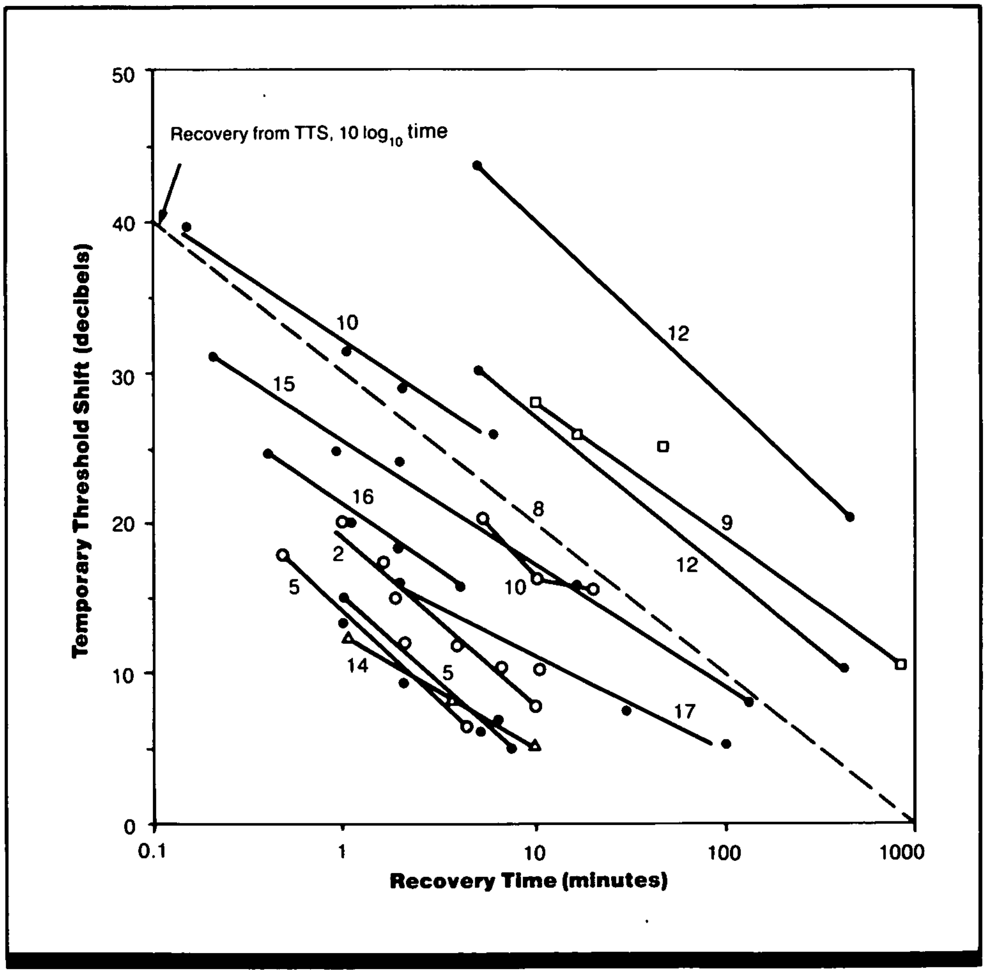

Figure 2. Recovery from temporary threshold shift as a function of time since exposure. Reference numbers on curves indicate sources of data points; see Table 1 for summary of test conditions. (From Ref. 8)

10.313 Temporary Threshold Shift: Effect of Noise Spectrum

Key Terms

Hearing loss; noise exposure; noise threshold; temporary threshold shift (TTS)

General Description

Temporary or permanent hearing loss (increases in threshold) can occur after exposure to high-intensity, narrow-band noise. The maximum temporary threshold shift (TTS) occurs at a signal frequency that is about 1/2 octave above the center frequency of the noise. Some noise control regulations have specified that ear protection is necessary at 95 dB when the noise does not contain a pure-tone component, if a pure-tone component is present. Although it is not clear that a pure-tone component increases TTS at frequencies >2000 Hz, low-frequency pure tones do increase TTS by relaxing the acoustic reflex (CRef. 2.202). The uniform 10-dB reduction for pure tones is too simple and increases the risk of permanent damage. Intensity, frequency, and duration should be considered when determining a correction factor to prevent damage. TTS for an individual *cannot* be predicted, even if the mean TTS values for a given exposure can be predicted (CRef. 10.316).

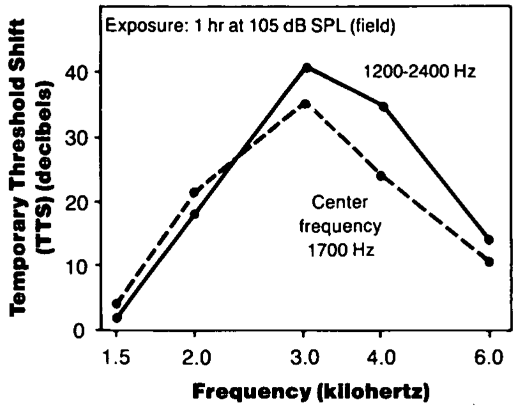

Figure 1. Temporary threshold shift as a function of frequency after exposure to 1200-2400-Hz octave-band noise or a narrow-bandwidth noise with 1700-Hz center frequency (Study 2). (From Ref. 2)

Methods

Test Conditions

Study 1 (Ref. 1)

- Octave noise bands centered at 500, 1000, 2000, and 4000 Hz; presented through loudspeakers to groups of 3-5 subjects at average noise levels of 75-88 dB SPL for 16-24 hr
- Thresholds measured by earphones, using sweep-frequency audiometry with gated tone on for 250 msec; thresholds measured once a day for 3 days before exposure, for 8-min intervals at prescribed times during exposure (subject removed from noise), and 4 min after exposure
- Individual thresholds determined by seven pre-exposure measurements of auditory sensitivity over the frequency range of 250-8000 Hz over 3 days prior to experiment

Study 2 (Ref. 2)

- Describes several studies: white noise at 105-dB SPL filtered with frequency cutoffs of 1200, 1700, 2400 Hz; five 1-min exposures to a 1700-Hz tone or 1200-2400-Hz noise at increasingly higher intensities; similar stimuli presented to one ear only with threshold measurements at other ear
- Thresholds determined using Rudmore ARJ-3 Békésy-type audiometer

Experimental Procedure

Study 1

- Modified method of limits (Békésy tracking procedure)
- Independent variables; center frequency of octave-band noise, frequency of test tone, exposure duration, exposure intensity
- Dependent variable: detection threshold of tone in quiet after exposure
- Subject's task: endure exposure; adjust tone to audible level after exposure
- 37 female and 23 male college students with hearing thresholds within ± 10 dB of the standard for 250-8000 Hz; subjects were nonsmokers, denied use of nonprescription drugs, and had negative medical and otological histories

Study 2

- Modified method of limits (Békésy tracking procedure)
- Independent variables: center frequency of noise, bandwidth of noise, length and intensity of exposure noise and threshold tests in same or different ears
- Dependent variable: signal threshold before and after exposure
- Subject's task: adjust tone to audible level
- Number of subjects not reported for data in Fig. 1; 12 adults with normal hearing used in other seven experiments (same subjects in all experiments)

Experimental Results

- Broadband noise can produce more TTS than narrowband noise.
- The maximum TTS is at a higher frequency (~1/2 octave) than the center frequency of the noise presented during the exposure phase of the experiment.
- Pure-tone components of noise increase the TTS if the pure tone is <2000 Hz, primarily by relaxing the acoustic reflect and therefore increasing the effective exposure. This is demonstrated by measuring the threshold of the unexposed ear, which undergoes the same acoustic reflex response as the exposed ear.
- Long-term exposures produce a steady increase in TTS up to ~1/2 octave above the center frequency as well as one at much higher frequency (e.g., 7000 Hz for 2000-Hz-centered noise, 6000 Hz for 1000-Hz-centered noise, and 5500 for 500-Hz-centered noise).
- Recovery from long-term exposure to 4.0 kHz-centered noise at several SPL's appears complete after 24-48 hr.

Variability

Study 1 reports considerable individual differences in the magnitude of the asymptotic threshold shift.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Does not apply to exposure to noise of individuals with existing hearing impairments. Additive effects of hearing loss are not known.
- Average data are described. Individual thresholds are not predictable due to large individual differences in effects of exposure.

Key References

*1. Mills, J. H., Gilbert, R. M., & Adkins, W. Y. (1979). Temporary threshold shifts in humans exposed to octave bands of noise for 16 to 24 hours. *Journal of the Acoustical Society of America, 65,* 1238-1248.

*2. Ward, W. D. (1962). Damage-risk criteria for line spectra. *Journal of the Acoustical Society of America, 34,* 1610-1619.

Cross References

2.202 Acoustic reflex;

2.301 Factors affecting auditory sensitivity in quiet;

10.311 Factors affecting the temporary threshold shift;

10.312 Temporary threshold shift and recovery time: effect of noise intensity;

10.314 Noise-induced hearing loss;

10.316 Prediction and prevention of hearing loss

10.314 Noise-Induced Hearing Loss

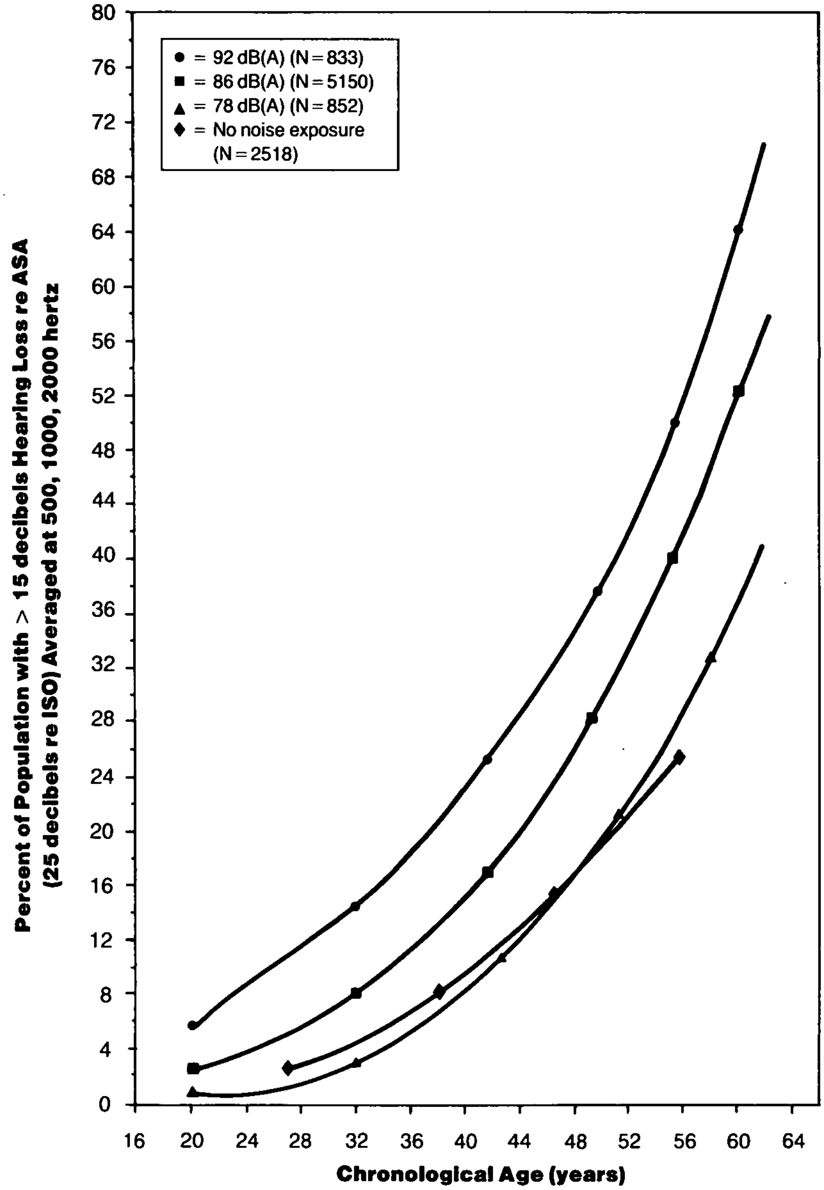

Figure 1. Incidence of right-ear hearing loss for male workers exposed 65% of work time to a range of 74-80 dB(A), 83-89 dB(A) or 89-95 dB(A) industrial noise (Study 1). (Legend identifies lines by averages and gives number of subjects.) Point for 60-65 age group calculated by extrapolation because of empirical data's high variability. No-noise curve is from a separate study cited in Ref. 1. (From Ref. 1)

Key Terms

Hearing loss; noise; noise intensity; noise-induced permanent threshold shift; temporary threshold shift (TTS)

General Description

Noise-induced hearing loss is a decrease in auditory sensitivity (i.e., an increase in threshold) as a result of exposure to noise in the environment, independent of age or disease. The loss can be a temporary threshold shift (TTS) or a noise-induced permanent threshold shift (NIPTS). Hearing loss increases as the intensity of the noise increases, as the length of exposure to noise increases, and as the bandwidth of the noise decreases (CRef. 10.315). Exposure to low-frequency noise produces the greatest loss of hearing (CRef. 10.315).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

Study 1 (Ref. 1)

- Environmental sound measured with sound level meter with (A) weighting network, set for slow response
- Stable work environments, in which subjects were exposed to noise between 74-80 dB(A), 83-89 dB(A), or 89-95 dB(A) for 65% of work time and to a wider range of intensities for the other 35% of the time; each exposure group broken into eight age groups; 18-23 yrs inclusive to 60-65 yrs inclusive
- Noise rich in low-frequency components similar to those in industry
- Audiograms conducted following Acoustical Society of America standards for 500, 1000, and 2000 Hz; hearing loss defined as >15 dB average decrement

Study 2 (Ref. 2)

- Noise measurements made by standard sound level meters supplemented by statistical analysis of noise distributions made from tape recordings
- Audiometric tests given to obtain nonmasked threshold readings within +5 dB of the International Standards Organization reference "O"
- Also, summarizes studies that examined a variety of industrial and environmental backgrounds

Experimental Procedure

Study 1

- Independent variables: intensity of exposure, age (equated with number of years of exposure through subject selection), ear (right or left), sex
- Dependent variables: amount of hearing loss, incidence of hearing loss (percentage of subjects showing >15 dB hearing loss)
- Subject's task: indicate when sound detected during audiogram
- 6835 male subjects

Study 2

- Independent variables: intensity of exposure, age
- Dependent variable: incidence of hearing loss
- Subject's task: indicate when sound detected during audiogram
- Subjects tested 14 hrs after last exposure to job noise to eliminate possible temporary effects
- Unknown numbers of subjects for most of these summarized studies

Experimental Results

- NIPTS increases with intensity of exposure.
- NIPTS increases with years of exposure, independent of age-related hearing loss (CRef. 2.303).
- Hearing loss is slightly greater in male left ears than in male right ears; hearing loss for females (either ear) is slightly less than for male right ears.
- NIPTS is frequency-dependent, in that lower frequencies produce greater loss. Low-frequency NIPTS is more serious because it raises thresholds in the frequency area of human speech (Ref. 6).
- NIPTS is greater from exposure to pure tones and narrow-band noise than from exposure to wide-band noise (Ref. 6).

Variability

Data for age group 60-65 from Study 1 were omitted because of extreme variability and small number of subjects. Maximum deviation of regression line from plotted data (Fig. 1) is −3% for one point; mean absolute deviation for 21 data points is 1.3%.

Repeatability/Comparison with Other Studies

The reported results are drawn from several different studies that yielded similar findings.

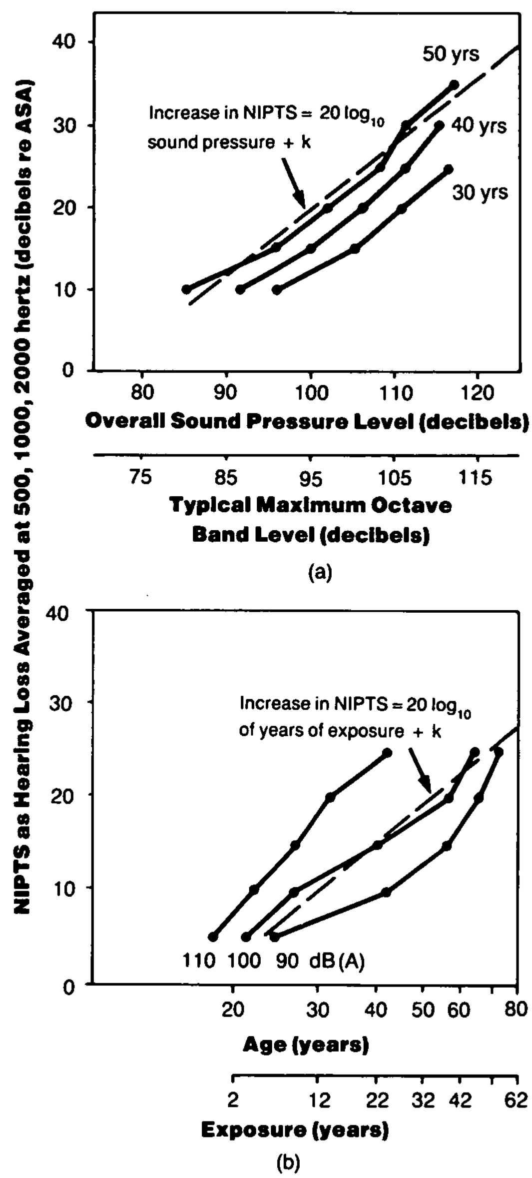

Figure 2. (a) Median noise-induced permanent threshold shift (NIPTS) for workers of different ages as a function of overall sound pressure level (SPL) of noise in dB(A) and octave-band maximum SPL. (b) Median NIPTS as a function of worker's age and duration of noise exposure at three noise intensities. (Adapted from data used for Fig. 1.) Dashed lines are estimated functions using formulas shown on figures. (From Ref. 5, based on Ref. 1)

Constraints

- Results are not corrected for natural aging (but thresholds can be compared with those in CRef. 2.303).
- NIPTS measurements can vary by as much as 10 dB because of differences in audiometer calibrations and differences in correction for age.

Key References

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5. Kryter, K. D. (1970). *The effects of noise on man*. New York: Academic Press.

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Cross References

2.104 Calibration procedures and instruments for measuring sound;

2.202 Acoustic reflex;

2.301 Factors affecting auditory sensitivity in quiet;

2.303 Auditory sensitivity in quiet: effect of age;

10.311 Factors affecting the temporary threshold shift;

10.315 Factors affecting noise-induced permanent threshold shift;

10.316 Prediction and prevention of hearing loss

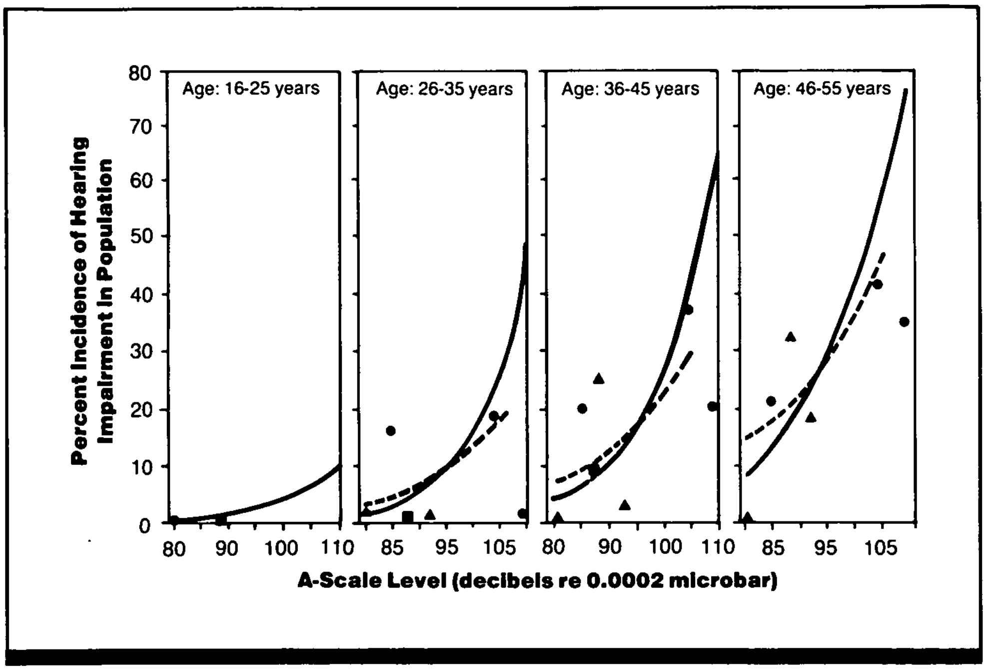

Figure 3. Incidence of hearing loss after exposure to industrial noise as a function of sound intensity and age. Hearing loss is specified as impairment greater than 20 dB at 500 Hz, 25 dB at 1000 Hz, and 30 dB at 2000 Hz; this International Standard Organization definition allows greater impairment than some other definitions of hearing loss. Solid lines are based on Study 1 (Ref. 1), data points are from Study 2 (Ref. 2), dashed curves are from a separate survey cited in Ref. 2. (From Ref. 2)

Notes

10.315 Factors Affecting Noise-Induced Permanent Threshold Shift

Factor	Manipulation	Effect	Source
Length of exposure	Test workers in noisy environments with unequal numbers of years on the job	Hearing loss is greater after longer exposures, although loss may level off after 10-14 yrs of exposure. (Corrections for age can be made when calculating NIPTS)	Refs. 1, 2, 3 CRef. 10.316
Intensity	Unequal overall sound pressure levels of noise	NIPTS increases as noise intensity increases 40 dB	Refs. 1, 2, 3 CRef. 10.316
Frequency/bandwidth	Different frequencies and sizes of noise bandwidth	The lower the frequency or the narrower the bandwidth, the greater the NIPTS	Refs. 2, 3
Energy distribution	Continuous versus impulsive noise	Both types of noise can produce NIPTS. However, NIPTS can be measured effectively only for steady-state noise because exposure duration can be calibrated. For impulsive noise, recovery increases as time between successive impulses increases, and thus NIPTS may not be equal across individuals for a given exposure.	Ref. 3
Individual differences	Non-experimental esposure to different frequencies, drugs, Vitamin A, or stapedectomy (removal of the stapes or stirrup bone from the middle ear)	There are large individual differences in susceptibility. In addition, individuals highly susceptible to damage at one frequency may not be as susceptible at another. Neither stapedectomy nor Vitamin A increases susceptibility, but oxygen deprivation and some antibiotics do, particularly at high noise frequencies. Susceptibility to TTS probably correlates with susceptibility to NIPTS, but this is mere conjecture	Ref. 3 CRef. 10.316

Key Terms

Hearing loss; masking; noise exposure; temporary threshold shift (TTS)

General Description

Exposure to noise of high intensity or for a long duration can cause permanent hearing loss at the frequencies contained in the noise. The degree of hearing loss increases as intensity or length of exposure increases. In addition, the lower the frequency and the narrower the bandwidth of noise, the greater the probable hearing loss.

Constraints

- Susceptibility to noise-induced permanent threshold shift (NIPTS) shows considerable individual differences.
- A person's degree of hearing loss at one frequency does not predict that person's susceptibility at other frequencies.
- Susceptibility may be related to overall health factors as well as physical status of auditory system prior to exposure.

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Key References

1. Baughn, W. L. (1966). Noise control—percent of population affected. *International Audio, 5*, 331-338.

2. Cohen, A., Anticaglia, J. R., & Jones, H. H. (1970). Noise-induced hearing loss: Exposures to steady-state noise. *Archives of Environmental Health, 20*, 614-623.

3. Kryter, K. D. (1970). *The effects of noise on man*. New York: Academic Press.

Cross References

2.613 Loudness discomfort level;

10.311 Factors affecting the temporary threshold shift;

10.314 Noise-induced hearing loss;

10.316 Prediction and prevention of hearing loss

10.316 Prediction and Prevention of Hearing Loss

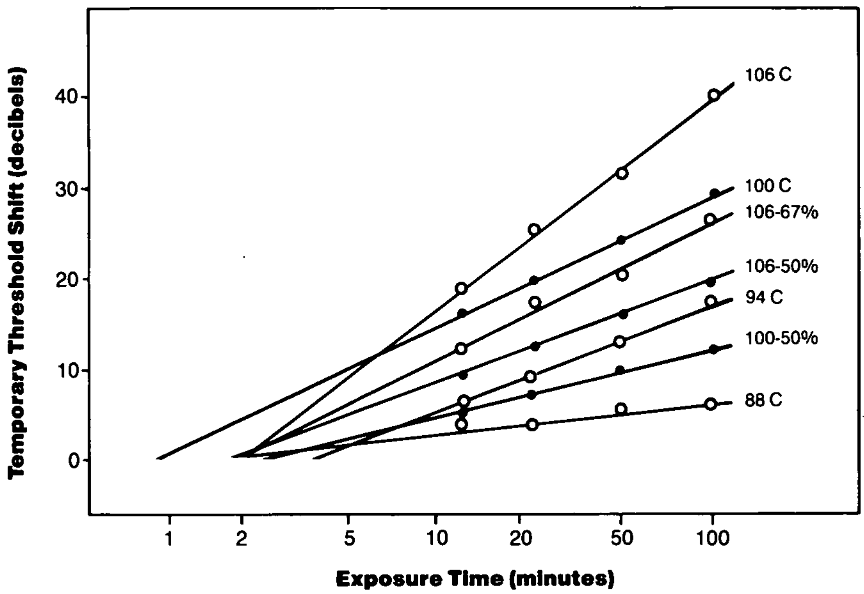

Figure 1. Temporary threshold shift (4000 Hz, 2 min after stimulation) as a function of exposure time with overall level (106, 100, 94, 88 SPL) and on-fraction (C indicates continuous) as parameters. Lines are least-squares solutions. (From Ref. 5)

Key Terms

Damage risk level; noise; noise intensity; noise-induced permanent threshold shift; temporary threshold shift

General Description

Long-term exposure or high-intensity noise causes a temporary threshold shift (TTS) that may become a noise-induced permanent threshold shift (NIPTS. i.e., a permanent hearing loss). In an effort to prevent TTS and thus NIPTS, researchers have proposed several ways of predicting when TTS will occur, given intensity and duration of noise exposure. However, these predictive methods are based on several assumptions that have not been thoroughly tested.

- A causal relation between TTS and NIPTS has not been established.
- Measurements of NIPTS may be off by as much as 10 dB due to differences in audiometer calibrations and corrections for hearing loss with age (Ref. 3; CRef. 10.315)
- Damage-risk contours are generated from short, intermittent noise exposure, and should not be generalized to other kinds of exposure.
- In addition, even if the average data can be predicted for any given situation, it is strongly emphasized that the risk of damage to hearing for an individual cannot be predicted because of large individual differences. That is, there is large variability about average predictions.

Two methods of prediction have been considered particularly useful under some conditions: the effective damage risk level (EDRL), which is based on damage-risk contours (Fig. 1 in Ref. 2), and the formulas of Ward and his associates for the growth of the recovery from TTS (Ref. 5). EDRL overestimates TTS, but is reasonably accurate when TTS is <30-40 dB and frequency is <4000 Hz; however, outside either of these boundaries, EDRL underestimates TTS and should not be used.

Ward et al. (Ref. 5) developed formulas that more successfully predict the average TTS growth and recovery. Growth of TTS is represented by: $TTS_t = A(\log_{10} T) + B$. TTS_t is the TTS t minutes after T minutes of noise exposure; the estimated parameters A and B differ with on-fraction and sound pressure level of the noise. Recovery is represented by: $TTS_t = A' (\log_{10} T) + B'$. These formulas describe the average effect at 4000 Hz of flat-by-octaves random noise on thresholds for normal young adults and they are subject to several limitations (Ref. 5): the TTS must be <50 dB. The equations either break down at short time exposures (<5 min) or have been tested only for 2-hr exposure durations. The equation for recovery does not hold for time-after-exposure <2 min. For noise with more than one SPL during the exposure, all SPLs must exceed 85 dB

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for duration of exposure. Bursts of noise must be >250 msec, but durations >1 min have not been tested.

There are three types of noise criteria used to limit noise exposure and thus prevent hearing damage: (1) damage-risk criteria, which are statements of relations among parameters used to describe noise exposure (e.g., duration, SPL) and hearing loss; (2) conservation criteria, which define noise limits that must be observed to conserve hearing ability; and (3) material design standards that regulate procured materials. These criteria vary for specific situations, and appropriate regulations should be consulted (e.g., Ref. 4 defines four airborne noise acceptance criteria and three structure-borne criteria).

Key References

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*3. Kryter, K. D., Ward, W. D., Miller, J. D., & Eldredge, D. H. (1965). Hazardous exposure to intermittent and steady-state noise. *Journal of the Acoustical Society of America, 39*, 451-464.

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Cross References

10.311 Factors affecting the temporary threshold shift;

10.312 Temporary threshold shift and recovery time: effect of noise intensity;

10.315 Factors affecting noise-induced permanent threshold shift

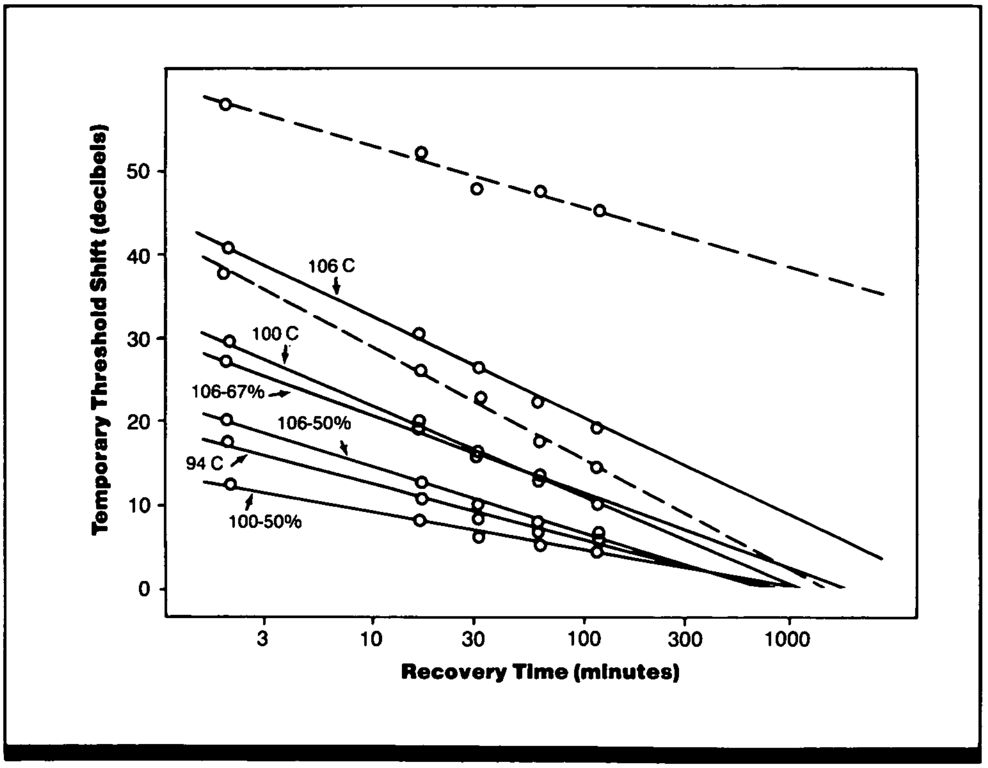

Figure 2. Recovering from temporary threshold shift (4000 Hz, 2-hour exposure) as a function of time with overall level (106, 100, 94 SPL) and on-fraction (C indicates continuous) as parameters. Dashed lines represent data from two subgroups at 106 C: upper curve represents 4 ears with initial TTS >50 dB; lower curve represents 22 ears with initial TTS <50 dB. Lines are least squares solutions. (From Ref. 5)

10.401 Vibration and Display Perception

General Description

The effect of vibration on performance depends upon the source of the motion, the type of motion, environmental conditions, the response of the individual, and the requirements placed upon the individual. Vibration may affect a person's specific performance, as well as produce subjective, biodynamic, and physiological effects. The extent of any adverse effect can be influenced by characteristics of the individual perceiving the effect, by changing the perceiver's objectives or response, or by modifying the cause or severity of the vibration. Most human vibration exposures result in a mingled relation between a complex motion and various effects.

Studies of human response to vibration have been conducted in field environments and in complex laboratory simulations. However, most of the basic information needed for equipment design results from simple systematic laboratory experiments; complex studies have rarely established useful cause-effect relationships or determined the effects of specific variables. Most studies have concentrated upon just one of the many specific aspects of vibration, whereas the acceptability of motion in an environment may depend on several variables and their interactions.

Precise guidance on the effects of vibration is often not possible. The most useful information shows the effects of changing the characteristics of the vibration (magnitude, frequency, etc.), the influence of modifying the transmission of vibration to the body (by seating and postural alterations), the sources and extent of individual variability, and the effects of alterations to the operator's task. The number of variables involved is usually so great that it is often possible to obtain some reduction of vibration effects by design changes which alter one or more variables.

Current vibration guides and standards vary in size and quality but do not give the comprehensive information required for all situations. The better documents provide information on how vibration conditions can be usefully quantified and reported; they may also provide sufficient information to guide designers in the general direction of optimum conditions.

The Vibration Environment

- Effects of vibration of the whole body (i.e., whole-body vibration) are usually expressed in terms of vibration measured at the interface between the body and the vibrating surface (CRefs. 10.402, 10.432); vibration of displays and hand controls may also need to be assessed (CRefs. 10.410, 10.411, 10.419, 10.420).
- Vertical vibration of seats is most frequently of interest, but other axes and input positions can be important (CRefs. 10.402, 10.408, 10.409, 10.429, 10.430). All effects of vibration depend on vibration frequency (CRefs. 10.402, 10.406, 10.409, 10.426, 10.430, 10.431); some effects are restricted to narrow ranges of frequency.
- Vibration magnitude can usually be expressed in terms of the root mean square (rms) acceleration (i.e., m/sec^2 rms) (CRef. 10.402); vibration magnitudes <0.01 m/sec^2 rms are not perceptible (CRef. 10.427); vibration magnitudes of 10 m/sec^2 rms and higher may be assumed to be dangerous (CRef. 10.430); motions containing occasional high magnitudes of acceleration should be quantified using peak, root mean quad (rmq), or other methods (CRefs. 10.402, 10.430).
- The influence of vibration duration has not been well studied (CRef. 10.402); current information shows small or inconsistent effects of vibration duration on task performance (CRef. 10.409); duration of vibration does affect discomfort, motion sickness, and health (CRefs. 10.426, 10.430).
- Vibration environments have complex motions which vary greatly in magnitude, frequency, direction, and duration (CRefs. 10.403, 10.404, 10.405); detailed analysis of motions (including vibration spectral analysis) is required when considering motion effects; the motions may produce several different effects or one dominant effect (CRefs. 10.409, 10.426, 10.429, 10.430).
- Seating conditions and body posture can greatly influence the magnitude and type of vibration transmitted to the body and the extent of adverse effects (CRefs. 10.406, 10.407, 10.408, 10.410, 10.427, 10.431, 10.432); seat dynamic response can be optimized by minimizing the transmission of vibration (CRef. 10.432); seat response depends on the impedance of the human body and cannot be determined without appropriate loading of the seat (CRef. 10.421).
- Effects of vibration can sometimes be related to vibration characteristics at specific locations on the body (e.g., eyes [CRef. 10.418], helmet [CRefs. 10.419, 10.420], shoulder [CRef. 10.421]).

Effects on Human Activities

- Vibration affects performance either by modifying how information is perceived or by influencing the control movements themselves. Impaired visual performance and limb control movements are most commonly documented (CRefs. 10.409, 10.410, 10.411, 10.412, 10.421, 10.423, 10.424).
- Impaired visual performance may arise from vibration of the eye (due to whole-body vibration or head vibration), vibration of the object being viewed, or simultaneous vibration of the eye and object (CRef. 10.411); the manner in which performance depends upon vibration frequency and vibration direction is different for these three viewing conditions (CRefs. 10.410, 10.411, 10.412).
- With low-frequency (<2.0 Hz) object vibration, vision is aided by pursuit eye movements; with higher frequencies of object vibration, vision is dependent on the perception of nodal images; with low and intermediate frequencies (<20 Hz) of rotational head motion, vision may be aided by compensatory eye movements arising from the vestibulo-ocular reflex (CRef. 10.418); compensatory eye movements are normally beneficial when viewing earth-fixed displays but are detrimental when viewing displays secured to the head (i.e., helmet-mounted displays) (CRef. 10.420); at high frequencies of head vibration

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(>20 Hz), some resonance of the eyes may occur within the head and contribute to degraded vision (CRef. 10.410).

- Effects of vibration on vision depend on viewing distance and whether any vibration of the eye is predominantly translational or rotational; a reduction in viewing distance will result in a beneficial increase in the angular subtense of displayed information when the eye motion is predominantly rotational; with low-frequency vibration and short viewing distances the effective eye motion is translational: reductions in viewing distance then result in a detrimental increase in the retinal image movement due to vibration; effects of low-frequency whole-body vibration on vision may be reduced by display collimation (CRef. 10.417).
- Vision becomes impaired by vibration when adjacent detail becomes confused or blurred; fine details (high spatial frequencies) are degraded the most, so legibility during vibration can be improved by increasing the size of viewed objects (CRef. 10.413); selection of the optimum character font is also advisable (CRef. 10.415); vertical and horizontal character spacing can be selected to minimize the overlap of character images during vibration (CRef. 10.414).
- Contrast should be fairly high to assist vision during vibration but should not exceed ~0.9; higher contrasts may degrade vision during vibration (CRef. 10.416).
- Hand control performance is most often degraded by vibration which causes a mechanical movement at the hand or by degradation in vision (CRef. 10.421); vibration may also interfere with neuromuscular processes or have a central nervous system effect; there may be a change of motivation or arousal or a deliberate change in the control of the system so as to minimize discomfort or avoid injury (CRef. 10.430); available models of the effects of vibration on manual control make many assumptions to aid simplicity.
- Vibration transmitted to the hand-control interface may degrade system performance if the system responds at the frequency of the vibration; the vibration response of the body often results in greatest vibration at the control of about 5 Hz (CRef. 10.422).
- Tasks involving hand positioning (either continuous movements such as those used to write, or discrete movements such as those used to operate a switch) are likely to be particularly sensitive to whole-body vibration at frequencies near 5 Hz (CRefs. 10.422, 10.424); low-frequency oscillation of the body (<1 Hz) can affect activities involving unsupported arm movements and tasks such as navigational plotting (CRef. 10.425).
- Many complex systems have a low response at frequencies >1 Hz; effects of higher frequency vibration are reduced by the use of first-order (or higher-order) controls (CRef. 10.422).
- The type of control and its sensitivity influence the effect of vibration on continuous manual control performance; the optimum control gain is lower in vibration environments than in static conditions; pure isometric controls tend to result in better performance than pure isotonic controls (CRef. 10.423).
- Effects of vibration on task performance depend on the relevant dependent performance measure (e.g., rms tracking error in 1 or 2 axes, rms vector error, mean error, time-on-target, distribution of periods of time-on-target); the study of the effects of vibration on continuous control performance requires consideration of the vibration-correlated error, the input-correlated error, and the error remnant (CRefs. 10.422, 10.423).

Subjective and Other Effects

- Motion sickness is often caused by low-frequency (<0.63 Hz) vertical oscillation; the greatest sensitivity to vibration acceleration occurs at ~0.1-0.3 Hz; at these frequencies 1 m/sec^2 rms may result in 10% vomiting incidence (CRef. 10.426).
- The prevalence of seasickness is greater in females than in males and greater in the young than in the old (CRef. 10.426); some habituation occurs with repeated exposure; motion sickness may interfere with activities (CRefs. 10.425, 10.426).
- Perception threshold for 2-100 Hz vibration is approximately 0.01 m/sec^2 rms for most axes of whole-body vibration and most orientations of the body (CRef. 10.427).
- At vibration magnitudes above threshold, discomfort (i.e., subjective magnitude) increases in linear proportion to the vibration magnitude (CRef. 10.428).
- Exposure of the entire body or parts of the body (e.g., limbs) to high magnitudes of continuous vibration or shock can cause injury or disease; the acceptable vibration magnitude depends on several factors including the vibration frequency, direction, duration, and point of contact with the body; general guidance is available but the probability of any specific injury due to given vibration conditions cannot be calculated (CRef. 10.430).
- Models exist for the prediction of vibration discomfort due to vibration occurring along 12 axes of the seated person (3 translational and 3 rotational axes on the seat, 3 translational axes at the seat back, 3 translational axes at the feet); other models are available for standing and lying persons; vibration discomfort can be predicted from the vibration at the interface between the body and the vibrating surface after it has been weighted according to the sensitivity of the body to the various vibration frequencies and the vibration axis; procedures have been defined for the summation of discomfort due to different input positions (CRef. 10.429).
- Root mean square measures of vibration magnitude may be used to predict discomfort when the vibration is continuous, of approximately constant magnitude, and does not contain shocks; different procedures have been defined for the evaluation of the discomfort of motions which vary with time or contain isolated or repeated shocks (CRef. 10.429).
- The vibration limit required to preserve comfort depends greatly on the context and also varies among individuals; guidance on the approximate predicted reaction to various magnitudes of vibration is available (CRefs. 10.428, 10.429).

Constraints

- Many factors influence human response to vibration.
- There are large differences in the responses of individuals to vibration due to physical differences (e.g., body dynamics), psychological differences (e.g., experience), and physiological differences (e.g., fitness).
- Appreciable changes in the response of an individual can occur over time due to alterations in body posture, habituation, or training.
- Occupational vibration exposures are highly variable; the vibration may differ greatly from moment to moment and from day to day; there may be large variations in the vibra-

tion measured in different vehicles of the same type; within individual vehicles, the vibration should be assumed to be different at different crew locations.

• The effects of translational vibration are most often studied, but rotational vibration can also have an important influence on response; rotational head motion may determine effects of vibration on vision; the translational vibration measured in vehicles and on the body may arise from vehicle rotations, and therefore increase with increases in distance from the center of rotation.

• Vertical vibration occurring on the seat is often assumed to be dominant, but other axes of motion and input locations can be more important; the combination of vibrations occurring in different axes and at different locations may be significant.

• Current models of human response to vibration make many assumptions and do not normally consider sources of inter- and intra-subject variability; complex models are difficult to use and do not always provide more accurate solutions than simple models; different models are required for the prediction of each different effect of vibration; some models do not clearly identify the response being modeled; models which identify the variables that relate cause and effect and models which indicate the relative importance of various causal parameters may often be most useful.

• Effects of vibration on activities are highly dependent on the nature of the task; it is not possible to make useful generalizations on the influence of vibration on task performance without defining the task.

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Cross References

10.402 Vibration measurement and representation;

10.403 Vibration characteristics of fixed-wing aircraft;

10.404 Vibration characteristics of rotary-wing aircraft;

10.405 Vibration characteristics of on- and off-road vehicles;

10.406 Factors affecting vibration transmission through the body;

10.407 Transmission of vertical seat vibration to the head;

10.408 Transmission of horizontal seat vibration to the head;

10.409 Factors affecting human performance during vibration;

10.410 Minimum amplitudes of vibration affecting vision;

10.411 Display legibility: effects of vibration frequency;

10.412 Visual performance: effect of random multiple-frequency and multiple-axis vibration;

10.413 Display legibility during vibration: effect of character subtense;

10.414 Display legibility during vibration: effect of character spacing;

10.415 Display legibility during vibration: effect of character font during whole-body vibration;

10.416 Display legibility during vibration: effect of luminance contrast;

10.417 Visual performance during whole-body vibration: effects of viewing distance and display collimation;

10.418 Transmission of vibration to the eyes;

10.419 Transmission of vibration to helmets;

10.420 Perception of information on helmet-mounted displays during vibration;

10.421 Model for predicting the effects of vibration on manual control performance;

10.422 Manual control performance: effects of system dynamics and vibration frequency;

10.423 Continuous manual control performance: interactive effects of control gain, control type, and vibration;

10.424 Data entry performance during vibration;

10.425 Manual control performance: effects of vertical z-axis oscillatory motion at frequencies below 1 Hz;

10.426 Factors affecting incidence of motion sickness caused by low-frequency vibration;

10.427 Vibration perception thresholds;

10.428 Effect of vibration magnitude on discomfort;

10.429 Model for predicting the discomfort of seated occupants of vehicles;

10.430 Effects of severe vibration;

10.431 Transmission of vibration through seats;

10.432 Comparison of the vibration isolation effectiveness of seats

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Notes

10.402 Vibration Measurement and Representation

Key Terms

Vibration analysis; vibration axis; vibration duration; vibration frequency; vibration magnitude

General Description

Effects of vibration on humans depend on the way vibration enters the body and is transmitted to the hands and head. A display's legibility depends on any motion of the display and the relative motion between the eyes of the observer and the display. Vibration in many environments is complex, with a range of vibration frequencies and magnitudes in many axes at several positions. The possible effects of vibration are also varied and complex.

Constraints

• Many factors influence the body's response to vibration; thus variability within and between subjects is generally significant.

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Cross References

10.403 Vibration characteristics of fixed-wing aircraft;

10.404 Vibration characteristics of rotary-wing aircraft;

10.405 Vibration characteristics of on-and-off-road vehicles;

10.407 Transmission of vertical seat vibration to the head;

10.408 Transmission of horizontal seat vibration to the head;

10.409 Factors affecting human performance during vibration;

10.410 Minimum amplitudes of vibration affecting vision;

10.411 Display legibility: effects of vibration frequency;

10.412 Visual performance: effect of random multiple-frequency and multiple-axis vibration;

10.417 Visual performance during whole-body vibration: effects of viewing distance and display collimation;

10.422 Manual control performance: effects of system dynamics and vibration frequency;

10.425 Manual control performance: effects of vertical z-axis oscillatory motion at frequencies below 1 hz;

10.426 Factors affecting incidence of motion sickness caused by low-frequency vibration;

10.427 Vibration perception thresholds;

10.429 Model for predicting the discomfort of seated occupants of vehicles;

10.430 Effects of severe vibration;

10.431 Transmission of vibration through seats;

10.432 Comparison of the vibration isolation effectiveness of seats

Factor	Significant Characteristics	Sources
Location	• Effects of body vibration measured at interface between body and vibrating surface (seat, floor, etc.)	Ref. 1
	• Measurements at other locations must be transformed to determine vibration at relevant body interface	CRef. 10.431
	• Effects of display vibration specified for vibration measured on the display	CRefs. 10.410, 10.411
	• Different vibration characteristics occur simultaneously at different locations (e.g., seat, seat back, feet, and display)	
	• Relative motion between two locations can be significant	CRefs. 10.411, 10.417
Axis	• Body responses are different for different axes of vibration	CRefs. 10.407, 10.408
	• For a seated or a standing observer, the three mutually orthogonal translational axes are: x-axis (fore-and-aft), y-axis (lateral), and z-axis (vertical)	CRefs. 10.428, 10.429, 10.430,
	• Rotational axes are: roll (rotation about x-axis), pitch (rotation about y-axis), and yaw (rotation about z-axis)	CRef. 10.429
	• Most coordinate systems are ***basicentric*** with origins at interface with body	

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Factor	Significant Characteristics	Sources
Frequency	• All vibration effects are highly frequency-dependent	CRefs. 10.411, 10,422, 10.425, 10,426, 10.427, 10.430
	• Frequencies <0.5 Hz associated with motion sickness	CRef. 10.426
	• Body resonances (∿4 to ∿20 Hz) associated with degraded vision, manual control, performance, and health	CRef. 10.409
	• Local vibration to hands (∿16 to ∿1000 Hz) associated with circulatory, bone, joint, muscle, and nerve injuries	CRef. 10.430
	• Response of seats may increase or decrease vibration depending on frequency	CRef. 10.432
	• Vibration environments contain characteristic vibration spectra with significant motion between ∿0.1 and ∿100 Hz	CRefs. 10.403 10.404, 10.405
	• Frequency content of motions often presented by acceleration power spectral densities	CRefs. 10.403, 10.404, 10.405
	• Body responses at every frequency weighted according to relative importance	CRefs. 10.412, 10.429, 10.430
	• Frequency weightings exist for several vibration effects	Ref. 1; CRefs. 10.412, 10.422, 10.426, 10.427, 10.429, 10.430
Magnitude	• Body vibration normally expressed as root mean square (rms) acceleration: m/sec^2 rms ($9.81\ m/sec^2 = 1\ g$)	Ref. 1
	• Severity of vibration (especially random and multiple frequency vibration) expressed by frequency-weighted rms acceleration	CRef. 10.429
	• ***crest factor*** is ratio of peak to rms of frequency-weighted acceleration	Ref. 2
	• rms acceleration underestimates severity of high crest factor motions	Ref. 2; CRef. 10.430
	• rmq (root mean quad) or vibration dose values may be used to assess subjective severity of high crest factor motions	CRef. 10.430
	• Threshold for visual detection of motion is dependent on retinal image displacement	CRef. 10.410
	• Reading performance dependent on velocity probability distribution of retinal image movement	CRef. 10.412
	• Vibration magnitudes $<0.01\ m/sec^2$ rms not perceptible	CRef. 10.427
	• Vibration magnitudes >1.0 to ∿5.0 m/sec^2 rms potentially hazardous, depending on duration	CRef. 10.430
Duration	• Limited published data on duration effects	
	• Retinal image movement produced by vibration unlikely to show large duration effects; other time-dependent effects on visual performance possible	CRef. 10.410
	• Published changes in manual control performance with duration may be explained by alterations in arousal and motivation	CRef. 10.409
	• Vibration perception thresholds assumed independent of duration	CRef. 10.427
	• Health effects dependent on duration	CRef. 10.430
	• Motion sickness increases with exposure duration up to ∿6 hr	CRef. 10.430
Transducers	• Vibration usually sensed by accelerometers	
	• Mass and shape of accelerometers must not alter vibration being measured	Ref. 1
	• Vibration at body interface measured with accelerometers in ***SAE pad*** or ***SIT-BAR***	Refs. 3, 4; CRef. 10.432
	• Accelerometer frequency response normally flat from ∿0 Hz to greater than ∿100 Hz	
Meters	• Sinusoidal vibration of known frequency indicated by rms meter	
	• Frequency analysis required for complex vibration	
Analysis	• Analysis depends on characteristics of motion and purpose of measurement	
	• Complex motions often expressed by acceleration power spectral densities [abscissa: Hz; ordinate: $(m/sec^2)^2/Hz$]	CRefs. 10.403, 10.404
	• Frequency resolution of power spectral densities must be present for magnitudes to be absolute	
	• Useful frequency resolutions ∿0.1 to 1.0 Hz	Ref. 1
	• Analysis of rms acceleration in ⅓-octave bands sometimes useful	
	• Frequency-weighting may be achieved by many alternative methods	
Presentation	• Measurements must indicate units (e.g., m/sec^2) and averaging method (e.g., rms)	
	• Measurements must indicate any frequency weighting employed	
	• Most non-sinusoidal motions require presentation of spectra	
	• Presentation should uniquely define measurement and analysis procedure	

10.403 Vibration Characteristics of Fixed-Wing Aircraft

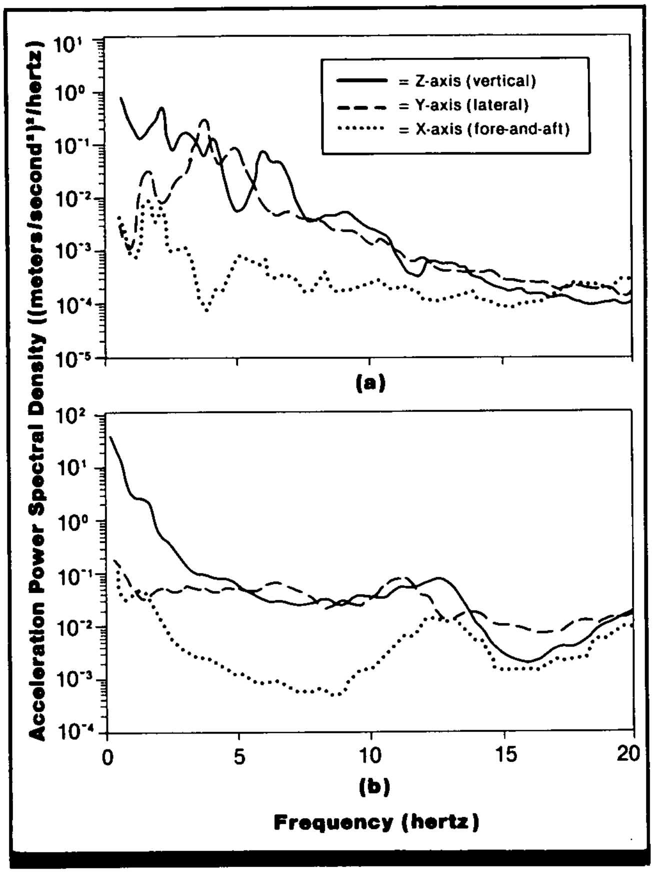

Figure 1. Power spectral densities of vibration acceleration in each of the translational axes at the cockpit floor of (a) a B-52 (resolution 0.2 Hz) (from Ref. 3); and (b) an F-4C (resolution 0.5 Hz) (from Ref. 2).

Key Terms

Aircraft simulation; aircraft vibration; cockpit vibration; turbulence; whole-body vibration

General Description

Translational cockpit vibration in the x-, y-, and z-axes in fixed-wing aircraft typically comprises a broadband random spectrum extending from 1-20 Hz or more. Acceleration amplitudes at low frequencies increase with atmospheric turbulence, especially in the vertical (z-) axis. Particularly high vibration acceleration amplitudes occur during low-altitude, high-speed flight, due to ground effect turbulence and pilot-induced accelerations in terrain-following maneuvers.

Flexible Bomber

Figure 1(a) shows power spectral density (psd) of vibration acceleration, measured in each of the translational axes, in a large, flexible bomber during low altitude (150 m) flight at Mach 0.55. Fairly sharp resonances are evident in the spectrum for each axis, due to flexibility of the airframe. At very low frequencies, vertical (z-axis) vibration predominates, but at >3 Hz the lateral (y-axis) and vertical vibration are of comparable amplitude.

Rigid Fighter

Figure 1(b) shows psd measured in the three translational axes, in a small and relatively rigid fighter during low altitude (30-150 m) flight at **transonic speeds** (Mach 1.0). At very low frequencies (<2 Hz) the vertical (z-axis) vibration acceleration power is greater than that in the large bomber. The fighter, flown at lower altitude and higher speed, was subjected to a higher gust input due to turbulence. There was also greater pilot-induced activity in following the terrain more closely and at higher speed. There are no well-defined resonances in the acceleration power spectra <10 Hz due to the rigid nature of the airframe. Lateral (y-axis) and vertical (z-axis) acceleration powers are similar (>3 Hz), as in the bomber.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Acceleration amplitudes depend upon atmospheric conditions, altitude, terrain, and speed, but frequency content typically remains similar.
- Vibration measurements were made on the airframe, close to crew stations. The vibration input to the aircrew will also depend on transmission of vibration through the seats (CRef. 10.431).
- In large, flexible aircraft, vibration may vary considerably between locations, depending on location of structural nodes of the airframe.

Key References

1. Bray, R. S., & Larson, W. F., (1965). *Simulator investigation of the problems of flying a swept-wing transport aircraft in heavy turbulence* (NASA-SP-83). Langley Air Force Base, VA: National Aeronautics and Space Administration.

*2. Speakman, J. D., Bonfili, H. F., Hille, H. R., & Cole, J. N. (1971). *Crew exposure in the F-4C aircraft during low altitude, high speed flight* (AMRL-TR-70-99). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory.

*3. Speakman, J. D., & Rose, J. F., (1971). *Crew compartment vibration environment in the B-52 aircraft during low altitude, high speed flight* (AMRL-TR-71-12). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory.

Cross References

10.431 Transmission of vibration through seats

10.404 Vibration Characteristics of Rotary-Wing Aircraft

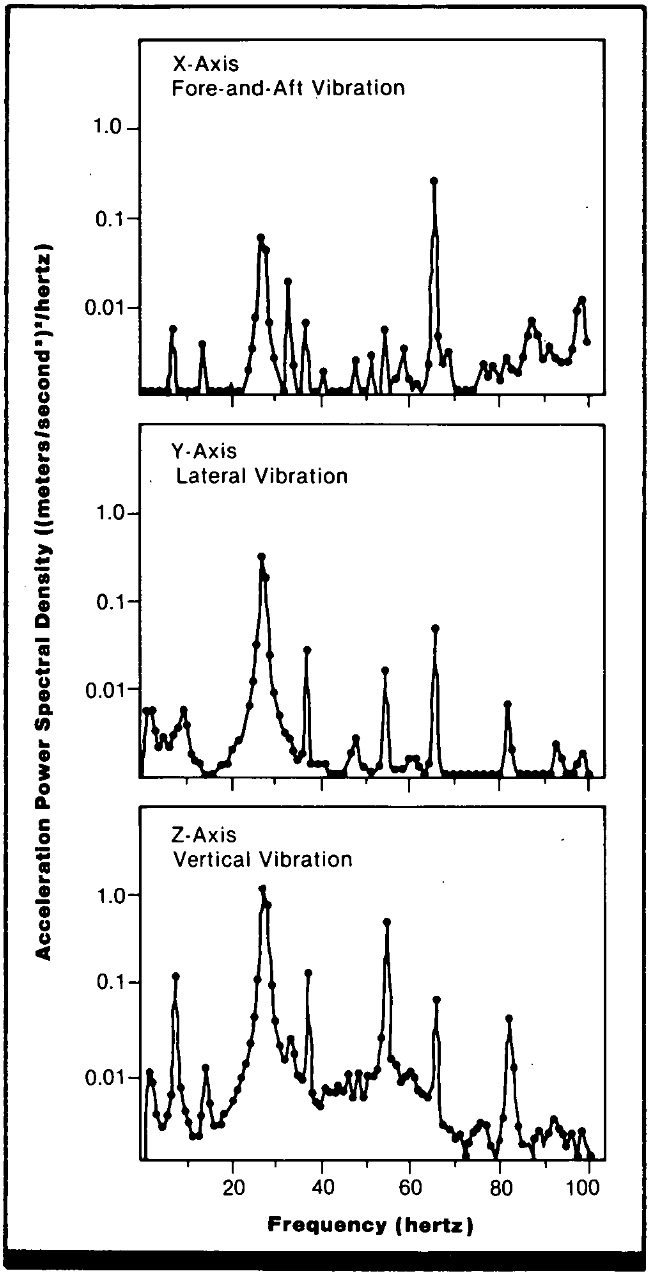

Figure 1. Power spectral densities of the vibration acceleration recorded in the translational axes at the cockpit floor of a Scout AH Mk 1 helicopter during forward flight at 50 m/sec (resolution = 1.0 Hz). (From Ref. 1)

Key Terms

Helicopter vibration; rotary wing aircraft; whole-body vibration

General Description

Vibration in the three translational (x-, y-, and z-) axes in the helicopter cockpit is dominated by a number of periodic components. The figure shows power spectral densities of vibration acceleration, measured in each translational axis, on the floor of a light, four-blade helicopter during 50 m/sec forward flight. Vibration frequencies can be associated with revolution rates of rotors, gearbox, engine, and other mechanical parts. Largest acceleration amplitudes typically occur at main rotor blade passage frequency (given by main rotor frequency multiplied by number of rotor blades). Other components occur at main rotor frequency (7 Hz), two times main rotor frequency, tail rotor frequency (32 Hz), tail rotor shaft frequency (37 Hz), eight times main rotor frequency, two times tail rotor frequency, and 12 times main rotor frequency.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Large variations in acceleration amplitudes of various frequency components can be observed during different flight modes. Greatest overall acceleration amplitudes frequently occur during maximum speed forward flight or during transition to hover from forward flight. Acceleration amplitudes within a particular helicopter tend to increase with increased speed and loading (Refs. 3, 5). Atmospheric turbulence and pilot-induced maneuvers (particularly in light, maneuverable helicopters) result in low-frequency, random accelerations which may affect performance and comfort (Ref. 5). Severity of the helicopter vibration tends to increase with the power of the helicopter (Ref. 5).

Constraints

- The figure refers to vibration acceleration measured at the helicopter floor, near the pilot seats. Effects of vibration on occupants depend upon seat transmission characteristics (CRef. 10.431).
- Amplitudes of floor vibration acceleration may vary considerably with location in the helicopter, depending on location of airframe structural nodes.
- Large variations occur in vibration acceleration amplitudes measured in apparently identical helicopters and, over time, in the same helicopter, due partly to maintenance.

Key References

*1. Griffin, M. J. (1972). *The transmission of tri-axial vibration to pilots in the Scout AH Mk 1 helicopter* (ISVR Technical Report No. 58). Southampton, England: University of Southampton, Institute of Sound and Vibration Research.

2. Griffin, M. J. (1974). *A study of vibration, pilot vision and helicopter accidents* (AGARD CP-145). Neuilly Sur Seine, France: Advisory Group for Aerospace Research and Development.

3. Grimster, W. F. (1974). *Pilot body vibration input on Sea-King helicopters* (Research Paper No. 475). Yeovil, England: Westland Helicopters Ltd.

4. Hixson, W. F., & Niven, J. I. (1969). *Sample helicopter flight motion data for vestibular reference* (NAMI-104). Pensacola, FL: Naval Aerospace Medical Institute.

5. Rance, B. M., & Chappelow, J. W. (1975). *Aircrew assessment of the vibration environment in helicopters* (AGARD CP-145). Neuilly Sur Seine, France: Advisory Group for Aerospace Research and Development.

Cross References

10.431 Transmission of vibration through seats

C - 5

10.405 Vibration Characteristics of On- and Off-Road Vehicles

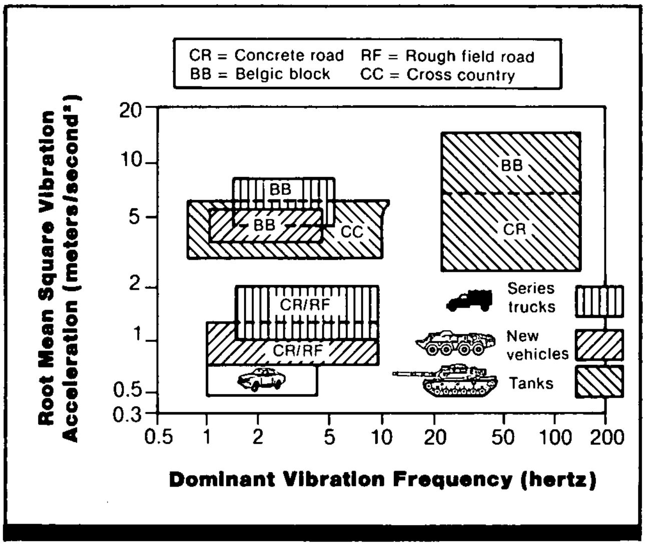

Figure 1. Unweighted root mean square acceleration amplitudes in the vertical (z-) axis on the seat, and the dominant vibration frequencies measured in military vehicles driven over different surfaces. (From Ref. 1)

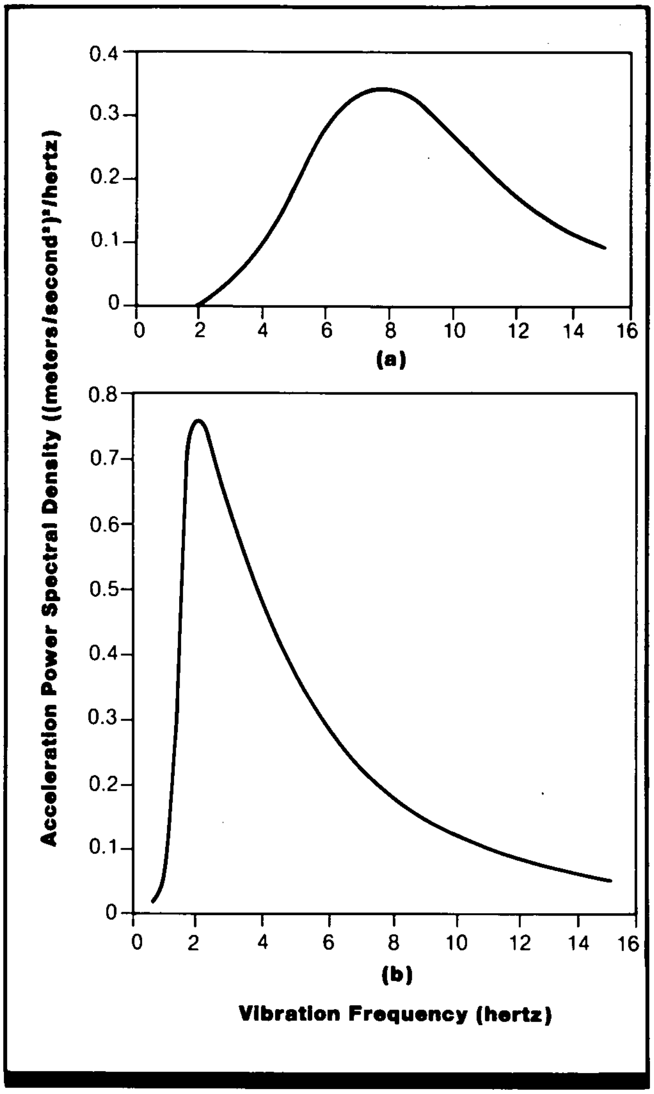

Figure 2. Standard acceleration power spectral density for (a) crawler tractor operating off-road; and (b) a wheel loader or wheel tractor operating off-road. (From Ref. 4)

Key Terms

Off-road vehicles; seat vibration; whole-body vibration

General Description

Translational vibration in on- and off-road vehicles is typically greatest in the vertical (z-) axis, particularly at frequencies <10 Hz which are most likely to affect human performance (CRef. 10.409).

Figure 1 indicates ranges of root mean square (rms) acceleration amplitudes (unweighted) and dominant frequencies which have been measured in the vertical axis between seat cushion and driver, in military vehicles driven over different surfaces. The Belgic block surface is a test road made of wooden blocks of different heights (Ref. 3).

Tracked Vehicles

On Belgic block and concrete roads, vertical seat vibration is dominated by track vibration at frequencies >20 Hz.

Low-frequency vibration occurs at high amplitude in tanks on cross-country surfaces, with acceleration peaks frequently exceeding 1 g. Figure 2a shows a standard acceleration power spectral density (psd) plot of vertical axis vibration of a crawler tractor during off-road operation. The spectrum defines vehicle structural vibration appropriate for seat testing purposes (Ref. 4).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Wheeled Vehicles

Vertical seat vibration in wheeled vehicles is dominated by frequencies from 1-6 Hz. Vibration acceleration amplitudes increase with surface roughness and vehicle speed. In conventional trucks over rough field roads, single acceleration peaks often exceed 1 g.

New-generation wheeled vehicles, with large balloon tires and optimized suspension systems, have lower dominant vibration frequencies than do conventional trucks. The rms acceleration levels also tend to be lower for similar surfaces. Figure 2b shows a standard acceleration psd plot of vertical axis vibration on the structure of a wheel loader or wheel tractor during off-road operation (Ref. 4).

Figure 3 compares the psd of vibration acceleration measured in each translational axis on the seat, seat-back, and floor of a car being driven over a rough, paved country road at 40 km/hr.

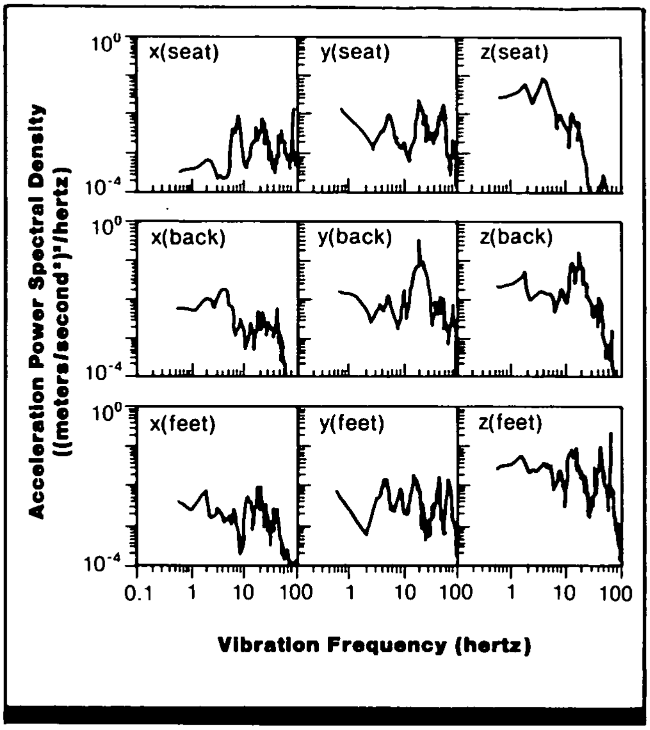

Figure 3. Acceleration power spectral densities measured in the three translational axes on the seat, seat-back, and floor of a car driven over a rough, paved road at 40 km/hr. (From Ref. 5)

Constraints

- Vertical vibration acceleration amplitudes on the seat depend on transmission through the seat, as well as on the vehicle's vibration characteristics. Figure 3 shows that the vertical vibration is amplified at 2-5 Hz, but attenuated at >5 Hz by this vehicle's seat. A well-designed seat tuned to take into account the vehicle's vibration spectrum may considerably reduce vibration acceleration amplitude at sensitive frequencies. Conversely, an inappropriate seat may increase the vibration acceleration amplitude at sensitive frequencies (Refs. 2, 4; CRef. 10.431). Figure 1 depicts unweighted rms acceleration amplitude on the seat. Effects of vibration on performance, comfort, and health depend on the frequency spectrum of the vibration (CRef. 10.429). To accurately account for differences in frequency sensitivity of tasks, etc., seat accelerations must be frequency-weighted before averaging (Ref 5; CRef. 10.429).

Key References

*1. Dupuis, H. (1974). *Human exposure to whole-body vibration in military vehicles and evaluation by application of* ISO/DIS 2631 (AGARD CP-145). Neuilly Sur Seine, France: Advisory Group for Aerospace Research and Development.

2. Griffin, M. J. (1978). The evaluation of vehicle vibration and seats. *Applied Ergonomics, 9,* 15-21.

3. International Standards Organization. (1979). *Agricultural wheeled tractors and field machinery — Measurement of whole-body vibration of the operator* (ISO 5008 - 1979 E). Geneva: ISO.

*4. International Standards Organization. (1980). *Earth moving machinery — operator seat — measurement of transmitted vibration* (Draft International Standard ISO 7096). Geneva: ISO.

*5. Parsons, K. C., & Griffin, M. J. (1983). *Methods for predicting passenger vibration discomfort* (SAE Technical Paper 831029). Warrendale, PA: Society of Automotive Engineers.

Cross References

10.409 Factors affecting human performance during vibration;

10.429 Model for predicting the discomfort of seated occupants of vehicles;

10.431 Transmission of vibration through seats

10.406 Factors Affecting Vibration Transmission Through the Body

Key Terms

Acceleration; hand controls; hand vibration; head position; head vibration; helmets; posture; seat belt; seat vibration; vibration transmission; whole-body vibration

General Description

Amplitudes of head and limb vibration of a seated person depend on vibration transmission through the body from the seat or other supporting surface.

Factor	Effect on Body Transmission	Source
Direction of seat vibration	Determines amplitudes and directions of head and limb vibration	CRefs. 10.407, 10.408
	Vibration in one direction at the seat may result in significant head and limb vibration in other directions	Refs. 1, 7
Vibration frequency	Vertical transmission through the torso is greatest between 3 and 5 Hz	CRefs. 10.407, 10.408
	Frequency of maximum transmission is increased by contact with a seat back	Refs. 1, 5
	Vertical transmission falls off rapidly at high frequencies	
Vibration amplitude	Little variation occurs with changes in vibration input amplitude if posture, contact with seat and harness, and other relevant factors are not modified	Refs. 1, 10
Posture and muscle tension	Vertical transmission to head greater with relaxed posture at <4 Hz	Refs. 2, 3, 10
	Vertical transmission to head greater with stiff, upright posture at >5 Hz	
	Five-fold change possible in vertical transmission to head at frequencies <100 Hz by controlling posture	
	Vertical transmission to shoulder less affected than to head	
Head position	Vertical transmission to head at frequencies <30 Hz increases on raising and decreases on lowering head	Ref. 3
Helmets and head mass	Vertical transmission to head reduced and pitch head motion increased by helmet at frequencies of 20-50 Hz	
Seat back and seat belt	Vertical head motion increased by contact with seat back and shoulder straps at frequencies >5 Hz	CRefs. 10.407, 10.408
	Pitch head motions increased by contact with seat back and shoulder straps at frequencies <60 Hz	Ref. 10
Sustained acceleration	Frequency of greatest vertical transmission through torso increased to 14 Hz during normal acceleration of 39 m/sec	Ref. 9
	Transmission through torso at frequencies <5 Hz reduced by sustained normal acceleration	
Characteristics of hand control	Less vibration-induced activity at frequencies >3 Hz is transmitted to hand when holding lightly-sprung displacement control compared to stiff force control	Refs. 1, 5, 6, 8
Position of hand control	Transmission to hand and control similar with center and side-mounted controls	Ref. 6
Body characteristics	Vertical transmission to head slightly greater in women than in men at frequencies >5 Hz and slightly greater in men than in women at frequencies <5 Hz	Ref. 4
	Vertical transmission to head negatively correlated with body weight at 16 Hz	

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Transmission of vibration from a vehicle to the head or limbs is also dependent on the transmission of vibration through the seat, which in turn is affected by body characteristics (CRef. 10.431).

• In all cases in the table, vertical head motion was measured at a bite-bar and includes a component due to rotational head motion, which is dependent on distance from the center of rotation of the head. However, the bite-bar is located in a vertical plane similar to that of the eye and should closely represent vertical vibration input to the eye.

• Vibration transmission to hands is also affected by factors affecting transmission of vibration to shoulders (Refs. 1, 8).

• Models provide useful analogues of body transmission characteristics in specific situations (Refs. 1, 8) but this general value may be limited by many factors affecting transmission of vibration through the body.

Key References

1. Allen, R. W., Jex, H. R., & Magdaleno, R. E. (1973). *Manual control performance and dynamic response during sinusoidal vibration* (AMRL-TR-73-78). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory. (DTIC No. AD773844)

2. Griffin, M. J. (1975). Vertical vibration of seated subjects: Effects of postures, vibration level and frequency. *Aviation, Space and Environmental Medicine, 46*, 269-276.

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10. Rowlands, G. F. (1977). *The transmission of .vertical vibration to the head and shoulders of seated men* (TR77068). Farnborough, England: Royal Aircraft Establishment.

Cross References

10.407 Transmission of vertical seat vibration to the head;

10.408 Transmission of horizontal seat vibration to the head;

10.431 Transmission of vibration through seats

10.407 Transmission of Vertical Seat Vibration to the Head

Key Terms

Body transmissibility; eye vibration; head vibration; seat vibration; visual acuity; whole-body vibration

General Description

Seat vibration in the vertical (z-) axis causes significant head vibration in both the vertical and pitch axes. The maximum vertical head vibration is produced by seat vibration frequencies of 3-8 Hz. Contact with seat backs and use of shoulder straps increase transmission of vibration to the head at frequencies >5 Hz.

Applications

Vibration transmitted through the body to the head and eyes produces a reduction in visual acuity by causing images to move on the retina (CRef. 10.410).

Methods

Test Conditions

- Two seating conditions: flat, rigid seat with no backrest and non-vibrating footrest; rigid seat with backrest, tight five-point harness, and vibrating footrest
- Subjects maintained constant upright, natural posture, looking straight ahead
- Seat excited separately in *x*- and *y*-axes with 2-64 Hz swept sinusoidal vibration; constant acceleration amplitude of 1.6 m/sec^2 root mean square.
- Head vibration measured by translational and rotational accelerometers mounted on a bite-bar gripped in the subject's teeth
- Transmissibilities computed from cross power spectral density (csd) of seat and head vibration divided by csd of seat vibration

Experimental Procedure

- Independent variables: seating conditions, axes excited, vibration frequency
- Dependent variable: amplitude of head vibration
- Subject's task: maintain constant upright, natural posture and look straight ahead
- 10 male subjects, ages 18-40

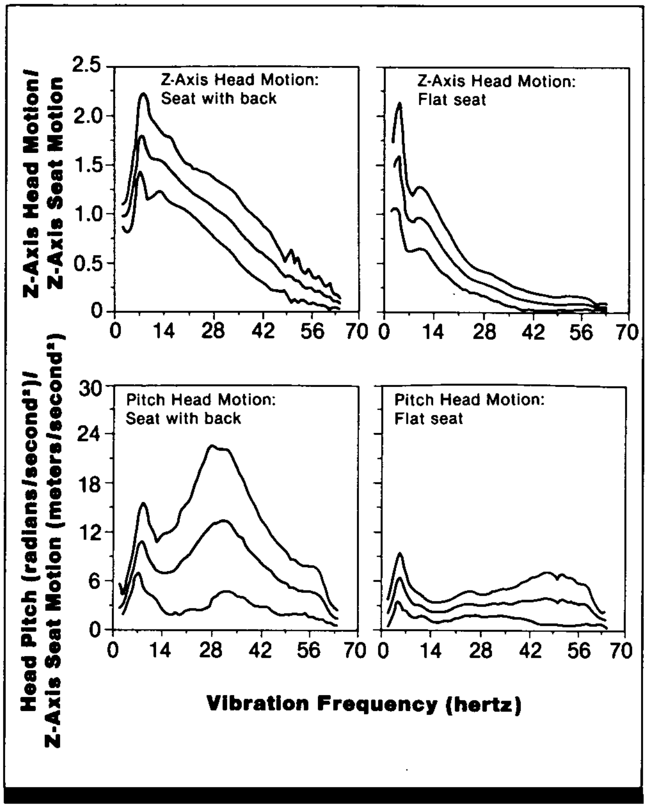

Figure 1. Transmissibility as a function of vibration frequency. Center curve is mean vibration amplitude; top and bottom curves are ±1 standard deviation. (From Ref. 3)

Experimental Results

- There is a peak in transmissibility for both vertical and pitch head vibration at seat vibration frequencies of 3-8 Hz. Vertical head vibration decreases with increasing vibration frequency >8 Hz, but there is a further increase in pitch axis head vibration at higher frequencies.
- Contact with seat back or use of shoulder straps increases transmissibility at frequencies >5 Hz. Transmissibility may be slightly reduced at lower frequencies.
- Large variations are found among subjects, particularly in pitch head motions at frequencies >10 Hz.
- Reference 4 reports phase lags between seat and head.

Constraints

- Vertical head motion measured at the bite-bar includes a component due to rotational head motion in pitch, and depends on distance of the bite-bar from head's center of rotation. However, the bite-bar is located in a vertical plane similar to that of the eye and should closely represent the vertical vibration input to the eye.
- Transmissibility curves in the figure only account for head vibration at the same frequency as seat vibration. At low frequencies, significant amounts of head vibration may also occur at the first harmonic of seat vibration.
- Head vibration is not an accurate predictor of eye vibration at all frequencies, since eye vibration is also dependent on transmission of vibration through supporting structures of the eye. The eye is actively pitch-axis stabilized at some frequencies (CRef. 10.418).
- Transmission of seat vibration to the head has also been shown to be affected by posture, muscle tension, body size, head position, sustained acceleration, and attachment of extra masses (such as helmets) to the head (CRef. 10.406).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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4. Rowlands, G. F. (1977). *The transmission of vertical vibration to the head and shoulders of seated men* (Technical Report TR-77068). Farnborough, England: Royal Aircraft Establishment.

Cross References

10.406 Factors affecting vibration transmission through the body;

10.408 Transmission of horizontal seat vibration to the head;

10.410 Minimum amplitudes of vibration affecting vision;

10.418 Transmission of vibration to the eyes;

10.431 Transmission of vibration through seats

10.408 Transmission of Horizontal Seat Vibration to the Head

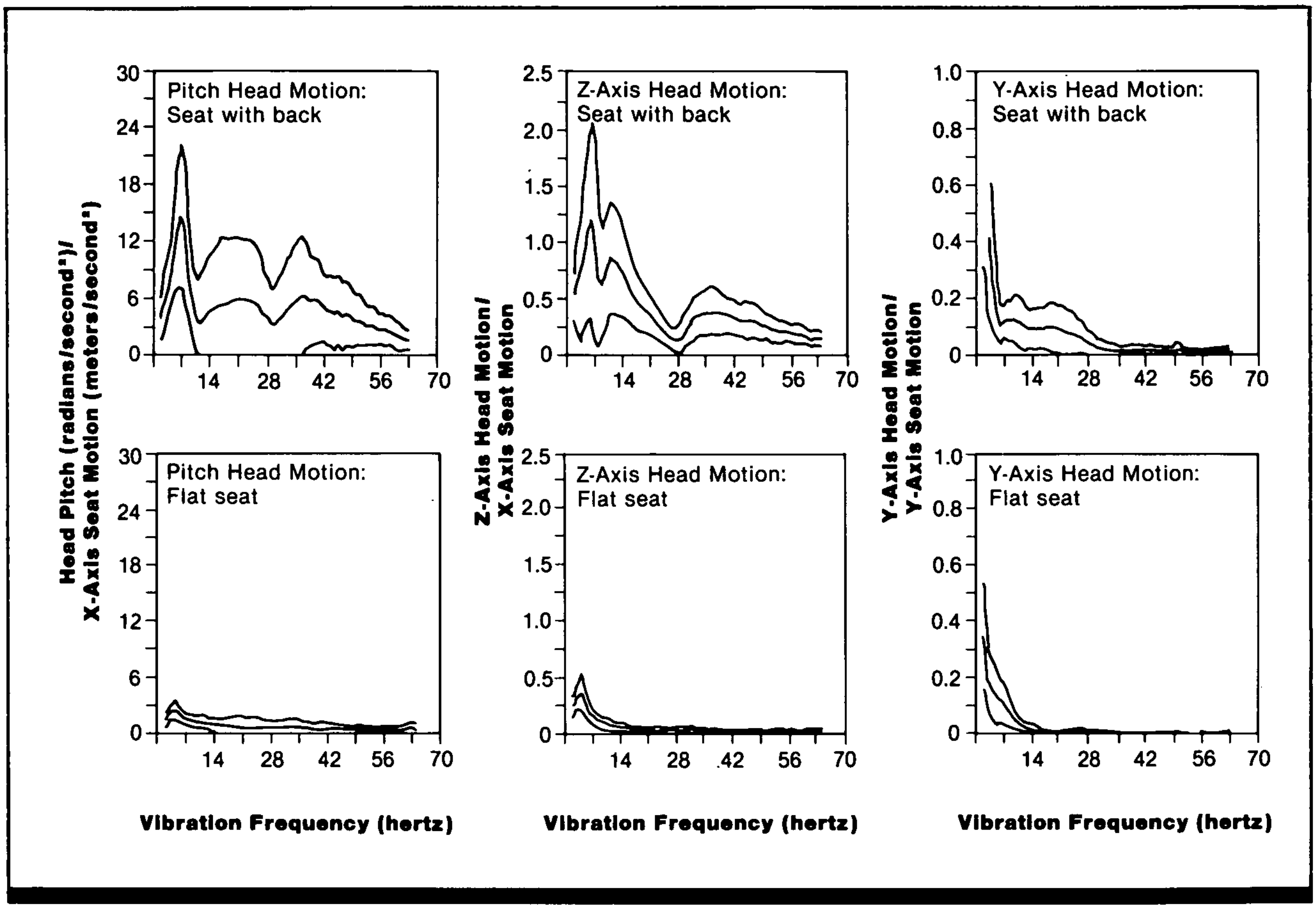


Figure 1. Transmissibility of horizontal seat vibration to the head. Center curve is mean vibration amplitude; upper and lower curves are ±1 standard deviation. (From Ref. 2)

Key Terms

Body transmissibility; eye vibration; head vibration; seat vibration; visual acuity; whole-body vibration

General Description

Horizontal (*x*- and *y*-axis) seat vibration causes head vibration in several translational and rotational axes. When there is no contact with the seat back, the head is well isolated from all but low-frequency horizontal seat vibration. Fore-and-aft (*x*-axis) seat back vibration induces significant pitch-axis head vibration, particularly at frequencies of 3-10 Hz, resulting in vertical motion in the plane of the eyes.

Applications

Vibration transmitted through body to head and eyes reduces visual acuity by causing retinal image motion (CRef. 10.410).

Methods

Test Conditions

- Seating conditions: flat, rigid seat with no backrest and non-vibrating footrest; rigid seat with backrest, tight five-point harness and vibrating footrest
- Subjects maintained constant, upright, natural posture, and looked straight ahead
- Seat excited separately in *x*- and *y*-axes with 2-64 Hz swept sinusoidal vibration; constant acceleration amplitude of 1.6 m/sec^2 root mean square
- Head vibration measured by translational and rotational accelerometers mounted on a bite-bar gripped in the subject's teeth
- Transmissibilities computed from cross power spectral density (csd) of seat and head vibration divided by csd of seat vibration

Experimental Procedure

- Independent variables: seating condition, axes excited, vibration frequency
- Dependent variable: amplitude of head vibration
- Subject's task: maintain constant, upright, natural posture, and look straight ahead
- 10 male subjects ages 18-40

Experimental Results

• Head is well isolated from lateral (*y*-axis) seat motion at all frequencies >2 Hz. Slightly more lateral vibration is transmitted to head when there is contact with the seat back and shoulder straps.
• Fore-and-aft (*x*-axis) seat motion induces rotational head vibration in the pitch axis. Transmissibility is typically greatest at 3-8 Hz, although there are large variations among individuals. Amplitude of pitch head vibration induced by *x*-axis seat vibration may be increased up to five times by contact with the seat back.
• Rotational head vibration in the pitch axis induced by *x*-axis seat vibration results in a significant vertical acceleration component at the bite-bar. Amplitude of the vertical component is dependent on distance of bite-bar from the head's center of rotation. However, since the bite-bar is located in a vertical plane similar to that of the eye, the vertical acceleration component should closely resemble vertical vibration input to the eye.

Constraints

• Head vibration is not an accurate predictor of eye vibration at all frequencies, since eye vibration is also dependent on transmission of vibration through the eye's supporting structures. The eye is actively stabilized in pitch axis at some frequencies (CRef. 10.418).
• Contact with a vibrating headrest may induce significant lateral head vibration, but may also stabilize the head in the pitch axis (Ref. 1).
• Transmissibility curves in the figure account only for the head vibration at the same frequency as seat vibration. At low frequencies, a significant degree of pitch axis head vibration may also occur at the first harmonic of seat vibration.
• Transmission of seat vibration to head is affected by additional factors, including posture, muscle tension, body size, and the attachment of extra masses (such as helmets) to the head (CRef. 10.406).

Key References

1. Johnston, M. E. (1979). *The effect of reclined seating on the transmission of linear vibration to the head* (Tech. Memo FS292). Farnborough, England: Royal Aircraft Establishment.

*2. Lewis, C. H., & Griffin, M. J. (1980). Predicting the effects of vibration frequency and axis, and seating conditions on the reading of numeric displays. *Ergonomics, 23,* 485-507.

Cross References

10.406 Factors affecting vibration transmission through the body;

10.407 Transmission of vertical seat vibration to the head;

10.410 Minimum amplitudes of vibration affecting vision;

10.418 Transmission of vibration to the eyes;

10.431 Transmission of vibration through seats

10.409 Factors Affecting Human Performance During Vibration

Key Terms

Alphanumeric displays; control dynamics; control sensitivity; display vibration; joysticks; legibility; manual control; rotary controls; task duration; vibration direction; vibration frequency; vibration transmission; whole-body vibration

General Description

Ability to see detail quickly and easily and ability to make precise control movements are greatly affected by vibration. The extent to which a visual task or manual control task is degraded by vibration depends on the nature of the vibration and the task, and other variables.

Factor	Effect on Performance	Source
Point of application of vibration	Visual performance is affected less by vibration <5 Hz when observer and display are vibrating together Vibration of display alone has a greater effect than vibration of observer alone	CRef. 10.411
Transmission of vibration through the body	Visual performance during whole-body vibration depends on amount of vibration transmitted to head and eyes Control performance also depends on amount of vibration transmitted to controlling limbs	CRef. 10.406
Display distance	Effects of translational eye or image motion decrease with viewing distance for the same angular image size Effects of rotational eye motion are independent of distance Display collimation (infinity focus) reduces effect of translational motion of eye or image	CRefs. 1.917, 10.417
Size of viewed image	Legibility of displayed symbols is severely degraded when image height is reduced below optimum value	CRefs. 10.413, 10.435
Spacing between viewed images	Reading performance degraded if spacing small enough for vibration-induced retinal image movement to cause overlapping of characters	CRefs. 10.414, 10.435
Shape of viewed image	7 x 9 pixel alphanumeric characters may result in superior reading performance to that with 5 x 7 pixel elements Character shape also affects character legibility under vibration	CRefs. 10.415, 10.435
Luminance contrast	High luminance contrast (>90%) may degrade reading performance during vibration	CRef. 10.416
Vibration frequency and amplitude distribution	Random vibration has smaller effect on visual performance than does sinusoidal vibration at the same root mean square (rms) magnitude Visual and manual control performance decrements in simple laboratory tasks may often be estimated from the rms sums of the frequency-weighted spectral components	Ref. 4; CRef. 10.412
Direction of vibration	Differential effects of vibration in different axes are largely due to differences in body transmission of vibration Dual axis vibration eliciting circular retinal image motion results in large decrements in visual performance	Refs. 1, 3, 6; CRef. 10.412

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Factor	Effect on Performance	Source
Control sensitivity	Optimum performance under vibration may be obtained with lower control sensitivities than in static conditions	CRef. 10.423
Control type	Force-operated, isometric controls may be affected more by vibration at frequencies >5 Hz than conventional spring-centered controls, due to greater amounts of vibration-induced control activity Effects of 4-Hz vibration on rotary controls are similar to effects on joysticks	Refs. 1, 3; CRef. 10.423
Control dynamics	Rate (i.e., first order) and higher order control dynamics progressively attenuate vibration-induced control activity compared with position (i.e., zero order) dynamics Tasks with higher order dynamics may be more sensitive to vibration effects other than direct vibration-induced activity	CRef. 10.422
Task duration and other stresses	Performance of non-arousing tasks may deteriorate less rapidly with duration during whole-body vibration than with no vibration Vibration may act as a non-specific stress and combine with other non-specific stresses, such as noise and heat, in a complex manner	Refs. 3, 5

Key References

1. Allen, W. A., Jex, H. R., & Magdaleno, R. E. (1973). *Manual control performance and dynamic response during sinusoidal vibration* (AMRL-TR-73-78). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory. (DTIC No. AD773844)

*2. Griffin, M. J., & Lewis, C. H. (1978). A review of the effects of vibration on visual acuity and continuous manual control, Part I: Visual acuity. *Journal of Sound and Vibration, 56*, 383-413.

*3. Lewis, C. H., & Griffin, M. J. (1978). A review of the effects of vibration on visual acuity and continuous manual control, Part II: Continuous manual control. *Journal of Sound and Vibration, 56*, 415-457.

4. Lewis, C. H., & Griffin, M. J. (1978). Predicting the effects of dual frequency vertical vibration on continuous manual control performance. *Ergonomics, 21*, 637-650.

5. Lewis, C. H., & Griffin, M. J. (1979). Mechanisms of the effects of vibration frequency, level and duration on continuous manual control performance. *Ergonomics, 22*, 855-889.

6. Lewis, C. H., & Griffin, M. J. (1980). Predicting the effects of vibration frequency and axis and seating conditions on the reading of numeric displays. *Ergonomics, 23*, 485-501.

Cross References

1.917 Factors affecting the vestibulo-ocular reflex;

10.406 Factors affecting vibration transmission through the body;

10.411 Display legibility: effects of vibration frequency;

10.412 Visual performance: effect of random multiple-frequency and multiple-axis vibration;

10.413 Display legibility during vibration: effect of character subtense;

10.414 Display legibility during vibration: effect of character spacing;

10.415 Display legibility during vibration: effect of character font during whole-body vibration;

10.416 Display legibility during vibration: effect of luminance contrast;

10.417 Visual performance during whole-body vibration: effects of viewing distance and display collimation;

10.422 Manual control performance: effects of system dynamics and vibration frequency;

10.423 Continuous manual control performance: interactive effects of control gain, control type, and vibration;

10.435 Spatial filtering descriptions of vibration-induced visual disruption

10.410 Minimum Amplitudes of Vibration Affecting Vision

Key Terms

Display vibration; eye vibration; head vibration; legibility; vibration transmission; visual blur; whole-body vibration

General Description

Observer vibration and/or target vibration may affect vision by producing moving retinal images that appear blurred. During observer vibration, factors which influence transmission of vibration to head and eyes also influence detection of visual blur (CRefs. 10.407, 10.418). These include posture, type of seat, axis of vibration, and variability between observers. Visual detection of target vibration by a stationary observer has been shown to depend on subtended vibration angle and, at frequencies >5 Hz, is independent of vibration frequency. The angle subtended at the retina is inversely proportional to viewing distance so, for a given amplitude of target vibration, increasing the viewing distance decreased the angular vibration, decreasing perception of target blur (CRef. 10.417).

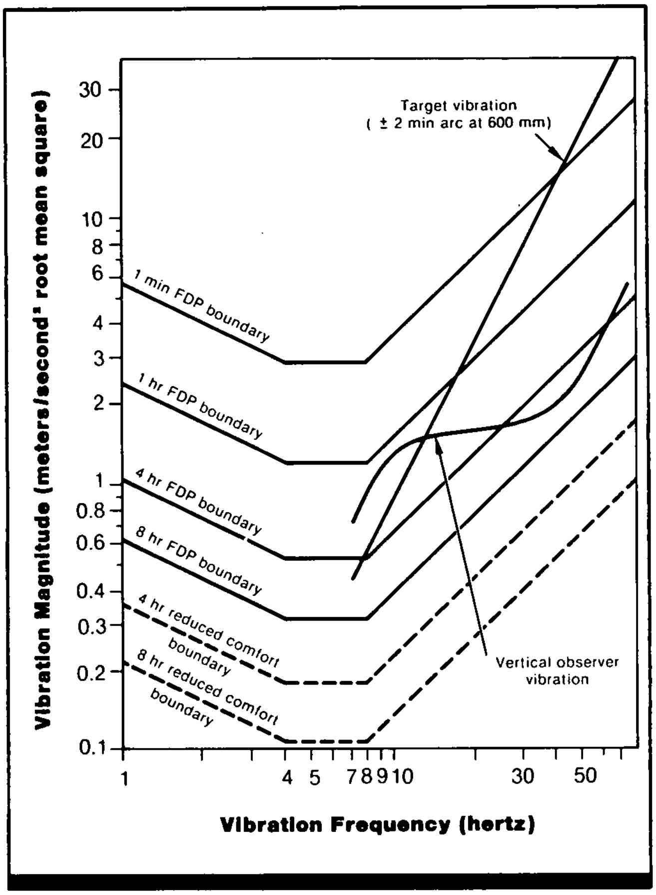


Figure 1. Mean amplitudes of observer vibration which produce visual blur of stationary point sources of light. (Amplitude of target vibration above which there may be an effect on reading ability = ~2 min arc of visual angle. Mean amplitude of target vibration required for detecting visual blur = ~1 min arc.) Also shown are the amplitudes of z-axis whole-body vibration from ISO 2631 (1978). FDP = Fatigue-Decreased Proficiency. (From Ref. 2)

Methods

Test Conditions

- Observer vibration experiment: vertical (z-axis) whole-body vibration applied to seated observer through a rigid (unpadded) flat seat, no backrest, a stationary footrest; 15 discrete sinusoidal frequencies between 7 and 75 Hz, generated with an electrodynamic vibrator
- Stationary target at 6-m viewing distance consisted of four 0.3-mm-diameter holes at the corners of a 200 x 200 mm square in a sheet of metal; hole illuminated from behind by a translucent screen (400 cd/m^2)
- Target vibration experiment: target of four 0.3-mm-diameter holes arranged at the corners of 100 x 100 mm square in a sheet of metal; holes illuminated from the rear by two 100-watt bulbs; target mounted on an electromagnetic vibrator
- Target viewing distances: 1.22, 2.44, 3.66, 4.88, and 6.1 m; four discrete sinusoidal frequencies at 7-20 Hz
- Observer vibration experiment: observers dark adapted for 20 minutes; 15 frequencies presented consecutively three times per session, two sessions per observer
- Target vibration experiment: all observers dark-adapted for approximately 20 minutes; 5 x 5 Latin square (observers x viewing distance or vibration frequency); six replications of each distance and frequency in two sessions; viewing distance followed by frequency

Experimental Procedure

- Method of adjustment
- Independent variables: vibration frequency, viewing distance
- Dependent variables: seat vibration amplitude, target vibration amplitude
- Observer's task: (observer vibration experiment) to adjust amplitude of vibration so there is definite blurring or movement and to maximize the sensation of vibration at the head (posturally); (target vibration experiment) to adjust target vibration amplitude to the minimum for definite target blurring or movement
- Observer vibration experiment: 12 male observers: research workers with >6/4 monocular vision; 6 observers used left eye, 6 observers used right eye
- Target vibration experiment: 5 male observers (all took part in observer vibration experiment); 2 observers used right eye, 3 observers used left eye

Experimental Results

- For observer vibration experiment, 2 of the 12 observers required seat vibration amplitudes higher than those allowed by the experiment (Observer 6 above 40 Hz; Observer 11 at 75 Hz). Mean amplitude of seat vibration is approximate to constant seat velocity. No more than 2 observers agreed on which frequency was "worst."
- For target vibration experiment, mean amplitude of target displacement was calculated from target root mean square acceleration. At constant frequency, mean vibration amplitude is approximately proportional to viewing distance. At constant viewing distance, average vibration acceleration amplitude is approximately proportional to the square of vibration frequency.
- Threshold for detection of vibration is approximately ~1 min arc of visual angle; vibration amplitudes greater than in the figure (~2 min arc) may, depending on the task, affect reading ability.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Variability

Observer vibration experiment: analysis of variance shows significant effect of frequency ($p<0.001$); standard deviations (SD) show large variability between observers; no main effect associated with repetitions at each frequency. Target vibration experiment: low variability is seen within and between observers; SD (worst case) is approximately 25% of the mean within 1 observer and 8% between observers at 5 Hz; 10% within 1 observer and 14% between observers at 20 Hz (6.1 m viewing distance).

Repeatability/Comparison with Other Studies

Target vibration: previous measurements of the detection of horizontal target vibration (Ref. 1) have determined amplitude sensitivities of approximately twice the amplitudes reported here. Experimental data (Ref. 2) suggest that the discrepancy may be due to differences in illumination (modified pupil diameter) between the two experiments.

Constraints

- Observer vibration experiment: in view of the great variability between observers, mean data should be applied carefully; vibration axis, observer posture, and location of vibration input to the observer (e.g., a seat back) may significantly affect amplitudes of vibration which will produce visual blur.
- The nature of the visual task will largely determine the effects of vibration on performance (CRefs. 10.413, 10.414, 10.416).
- In situations where both the target and the observer are vibrating, the minimum amplitudes of vibration affecting vision may change (CRef. 10.411).

Key References

1. Crook, M. N., Harker, G. S., Hoffman, A. C., Wulfeck, J. W., & Kennedy, J. L. (1949). *A determination of amplitude thresholds for the visual perception of vibration* (MCREXD-694-1R). Wright-Patterson Air Force Base, OH: USAF Air Material Command. (DTIC No. ADF630359)

*2. Griffin, M. J. (1973). *Whole-body vibration and human vision.* Unpublished doctoral dissertation, University of Southampton, England.

3. Griffin, M. J. (1975). Levels of whole-body vibration affecting human vision. *Aviation, Space and Environmental Medicine, 46,* 1033-1040.

Cross References

10.407 Transmission of vertical seat vibration to the head;

10.411 Display legibility: effects of vibration frequency;

10.413 Display legibility during vibration: effect of character subtense;

10.414 Display legibility during vibration: effect of character spacing;

10.416 Display legibility during vibration: effect of luminance contrast;

10.417 Visual performance during whole-body vibration: effects of viewing distance and display collimation;

10.418 Transmission of vibration to the eyes;

10.435 Spatial filtering descriptions of vibration-induced visual disruption;

11.105 CRT-image motion: effect on target identification;

11.106 CRT-image motion: effect on target detection;

11.115 Dot matrix displays: effect of interpixel spacing on character identification;

11.209 Alphanumeric font and display legibility

10.411 Display Legibility: Effects of Vibration Frequency

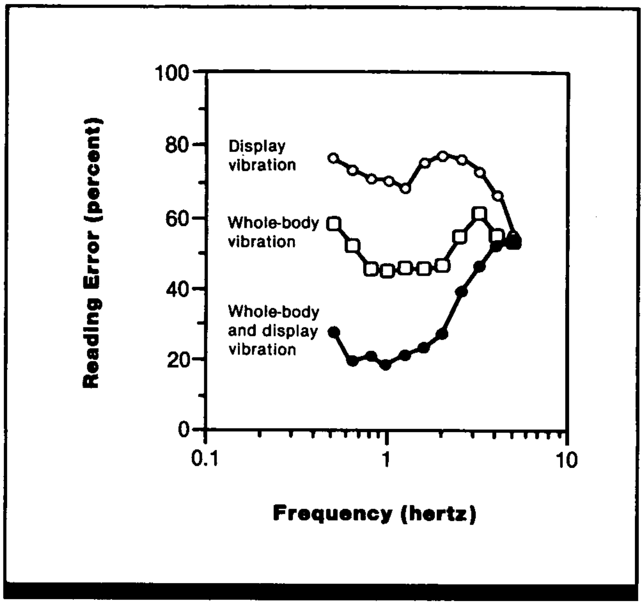


Figure 1. Reading error for three display viewing conditions (Study 1), 0.5-5 Hz. (From Ref. 4)

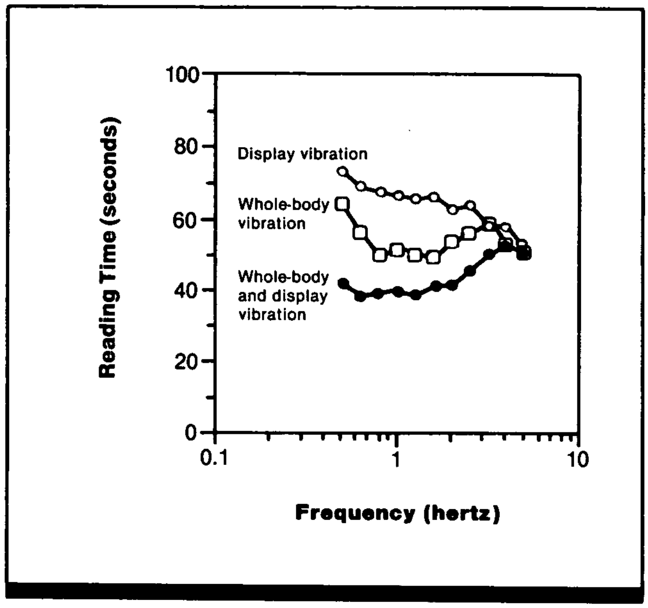


Figure 2. Reading time for three display viewing conditions (Study 1), 0.5-5 Hz. (From Ref. 4)

Key Terms

Display vibration; equal performance contours; head-down displays; legibility; reading error; whole-body vibration

General Description

Vibration-degraded display legibility is a function of vibration frequency and also depends on whether only the observer, only the display, or both observer and display are vibrating. At frequencies <3.15 Hz, display-only vibration results in the greatest loss of legibility, and observer-and-display vibration results in the least. At frequencies of 3.15 and 5.0 Hz, differences between the three display conditions are insignificant. For observer-only vibration at high frequencies, the greatest performance losses occur between 5.6-11.2 Hz.

Applications

Panel-mounted, **head-down displays** with an alphanumeric content situated in environments subject to vibration, e.g., fixed and rotary wing aircraft.

Methods

Test Conditions

Study 1 (Ref. 4)

- 5 x 10 array of 50 light numerals on a dark background monochrome video monitor; symbol luminance = 7 cd/m^2; luminance contrast >90%, angular subtense of characters = 5 min arc of visual angle; binocular viewing. Vibration condition: whole-body, display, whole-body and display
- Vibration stimuli presented vertically (z-axis) to observers seated on hard flat seats; binocular viewing
- Frequency range 0.5-5.0 Hz **acceleration magnitude** 2.5 m/sec^2 root mean square (rms)

Study 2 (Ref. 2)

- 5 x 10 array of 50 light numerals on a dark background monochrome video monitor; symbol luminance = 19.2 cd/m^2; luminance contrast >90%; angular subtense of characters = 5 min arc; binocular viewing
- Vibration conditions: whole-body, display, whole-body and display
- Vibration presented vertically to subjects on simulated helicopter seat with backrest
- Frequency range 0.5-5 Hz; acceleration magnitude 0.56-8 m/sec^2 rms

Experimental Procedure

- Independent variables: vibration frequency, vibration magnitude, vibration (of display, observer, both)
- Dependent variables: reading errors, reading time
- Subject's task: (Study 1) read display of 50 numerals as fast and as accurately as possible (Study 2); read numerals paced at 1 character/sec
- Study 1: 15 subjects; Study 2: 10 college students and staff, some practice

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Mean data indicate that, at frequencies <3-4 Hz, display-only vibration is responsible for the greatest display degradation and observer and display vibration the least ($p<0.001$).
- At frequencies >3-4 Hz the difference between the three viewing conditions is not significant.
- Similarity in the extent of display degradation for the three viewing conditions at frequencies >3.15 Hz suggests that display parameter studies using observer-only vibration in the 3.15 Hz region will be applicable to display-only and observer-and-display viewing conditions (CRefs. 10.413, 10.414, 10.415, 10.416).
- Observer only vibration at high frequencies produces largest decrements in the 5.6-11.2-Hz region. At frequencies >11.2 Hz, performance substantially improves with increased vibration frequency.

Variability

Study 1: No information on variability was given. Study 2: 95% confidence intervals are provided in Ref. 2.

Repeatability/Comparison with Other Studies

Reference 3 identifies a relationship between reading errors and vibration frequency similar to that in Fig. 2.

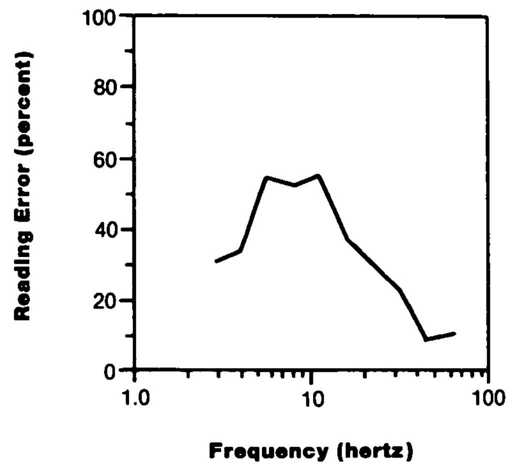


Figure 3. Reading error (Study 2): whole-body vibration, 2.8-63 Hz. (From Ref. 2)

Constraints

- The extent of display degradation is dependent not only on vibration frequency and viewing conditions but also on the vibration stimulus waveforms, axis of vibration (CRef. 10.412), and parameters of the display (CRefs. 10.413, 10.414, 10.415, 10.416).
- Reference 1 suggests that, at high frequencies (14-27 Hz), observer-only vibration will (due to eye resonances) produce a greater loss of legibility than display vibration.

Key References

1. Dennis, J. P. (1965). Some effects of vibration on visual performance. *Journal of Applied Psychology, 49*, 245-252.

*2. Furness, T. A. (1981). *The effects of whole-body vibration on the perception of the helmet-mounted display*. Unpublished doctoral dissertation, University of Southampton, England.

3. Lewis, C. H., & Griffin, M. J. (1980). Predicting the effects of vertical vibration frequency, combinations of frequencies and viewing distance on the reading of numeric displays. *Journal of Sound and Vibration, 70*, 355-377.

*4. Moseley, M. J., & Griffin, M. J. (1986). Effects of display vibration and whole body vibration on visual performance. *Ergonomics, 29*, 977-983.

Cross References

10.409 Factors affecting human performance during vibration;

10.410 Minimum amplitudes of vibration affecting vision;

10.412 Visual performance: effect of random multiple-frequency and multiple-axis vibration;

10.413 Display legibility during vibration: effect of character subtense;

10.414 Display legibility during vibration: effect of character spacing;

10.415 Display legibility during vibration: effect of character font during whole-body vibration;

10.416 Display legibility during vibration: effect of luminance contrast

10.412 Visual Performance: Effect of Random Multiple-Frequency and Multiple-Axis Vibration

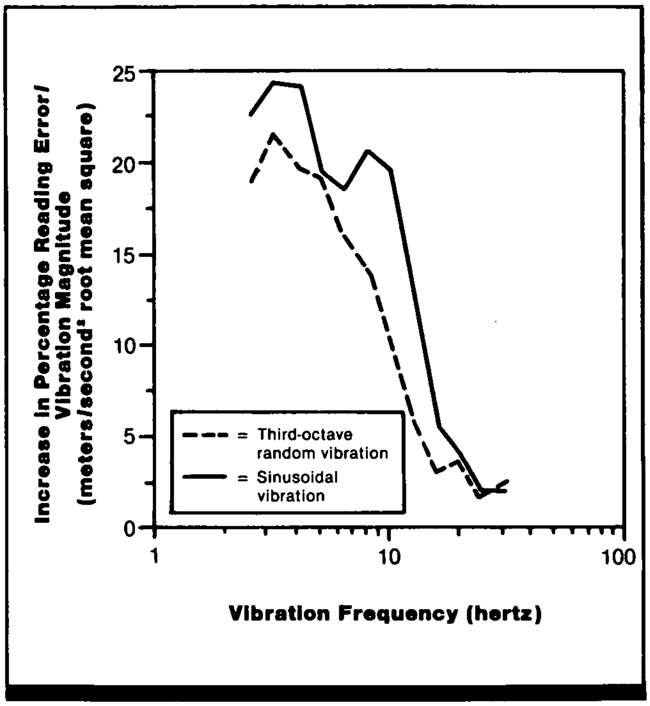


Figure 1. Effect of 1/3-octave random and sinusoidal vibration on visual performance (Study 1). (From Ref. 4)

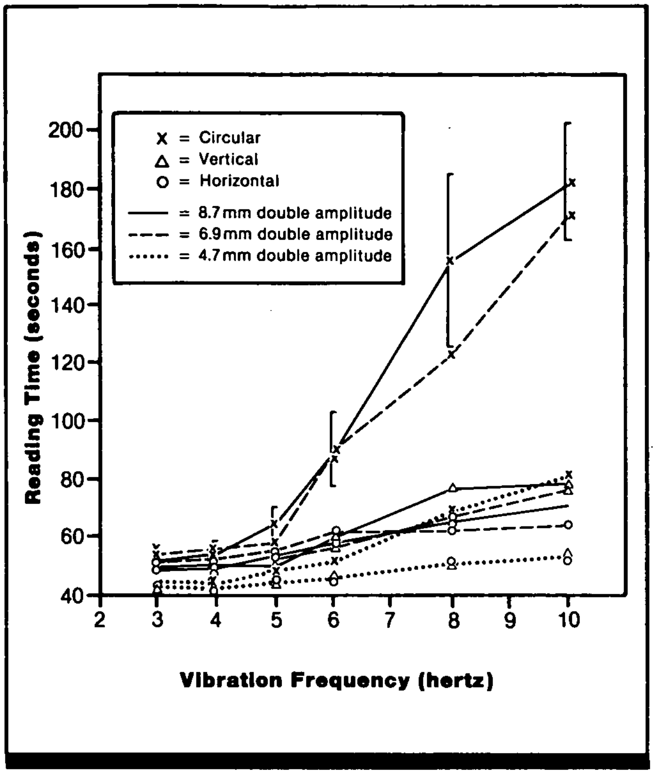


Figure 2. Effect of vertical, horizontal, and dual axis (circular) vibration on visual performance (Study 2). (From Ref. 3)

Key Terms

Display vibration; legibility; multi-axis vibration; whole-body vibration

General Description

In the frequency range of 2.5-25 Hz, 1/3-octave-band random whole-body vibration produces less severe degradation of visual performance than does sinusoidal whole-body vibration. At all frequencies except 3 Hz, a greater number of reading errors occurs with dual-axis (circular) vibration of display material than with single-axis sinusoidal motion alone.

Applications

Estimating instrument and display legibility in environments subject to vibration.

Methods

Test Conditions

Study 1 (Ref. 4)

- 5 x 10 array of 50 light numerals, five of each numeral, randomly arranged, presented on a dark background on monochrome video monitor and a hard-copy 10 x 10 array of 100 numerals, 10 of each numeral, in pixels, symbol luminance of 7 cd/m²; luminance contrast >90%; viewing distance of 0.75 m
- Whole-body vibration
- Vibration waveform: sinusoidal or 1/3-octave-band random; vertical axis: frequency range of 2.5-31.5 Hz; acceleration magnitude 1.8-4 m/sec² root mean square; data normalized for magnitude

Study 2 (Ref. 3)

- British Standard 3693A numerals at 3750 lux/m illumination; 1 m viewing distance, binocular viewing, subject stationary
- Display vibrating on vertical or horizontal axis, or both, at frequencies between 3 and 10 Hz; double amplitude displacement of 0.0047-0.0087 m

Experimental Procedure

- Repeated measures
- Independent variables: Study 1: 1/3-octave-band random or sinusoidal whole-body vibration, vibration frequency; Study 2: vibration frequency, double amplitude displacement, single or dual axis vibration
- Dependent variables: number of reading errors, reading time
- Subject's task: Study 1: paced reading of numerals at 1 character/sec; Study 2: observer instructed to read as fast as possible omitting no numerals
- Study 1: 12 subjects; Study 2: 9 subjects, college students and staff, some practice

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Study 1 mean data indicate that 1/3-octave-band random whole-body vibration produces a less severe effect on visual performance than sinusoidal whole-body vibration equated for vibration magnitude ($p < 0.01$). Analysis at each individual frequency reveals difference in effects of the two motions to be significant only at 10 Hz ($p < 0.001$). Error under static (no vibration) conditions is: mean = 10.3%, standard deviation = 5.7%, range = 0-20%.
- Study 2 data indicate that at all frequencies except 3 Hz, a significantly greater number of error occurs during dual-axis (circular) vibration than during horizontal or vertical vibration alone ($p < 0.05$).
- Other sources (Refs. 1, 2) show that multiple frequency vibration produces a less severe effect on visual performance than the most severe component alone.

Variability

For Study 1: Ref. 4 provides individual data for each observer. No other dispersion measures provided. For Study 2: standard deviations for 0.00817 m dual-axis motion indicated in Fig. 2.

Repeatability/Comparison with Other Studies

No other studies to date have directly compared sinusoidal and random vibration over a range of frequencies.

Constraints

- Differences between sinusoidal and random vibration may vary with task and instructions; e.g., in an unpaced task with random motion observers might wait for periods of low-image velocity before attempting to read test material.

Key References

1. Alexander, C. (1972). *Performance changes due to the single axis dual frequency vibration of reading material.* Unpublished master's thesis, University of Southampton, Southampton, England.

2. Lewis, C. H., & Griffin, M. H. (1980). Predicting the effects of vertical vibration frequency, combinations of frequencies and viewing distance on the reading of numeric displays. *Journal of Sound Vibrations, 70*, 355-377.

*3. Meddick, R. D. L., & Griffin, M. J. (1976). The effect of two-axis vibration on the legibility of reading material. *Ergonomics, 19*, 22-23.

*4. Moseley, M. J., Lewis, C. H., & Griffin, M. J. (1982). Sinusoidal and random whole-body vibration: Comparative effects of visual performance. *Aviation, Space, and Environmental Medicine, 53*, 1000-1005.

Cross References

10.409 Factors affecting human performance during vibration;

10.411 Display legibility: effects of vibration frequency;

11.209 Alphanumeric font and display legibility

10.413 Display Legibility During Vibration: Effect of Character Subtense

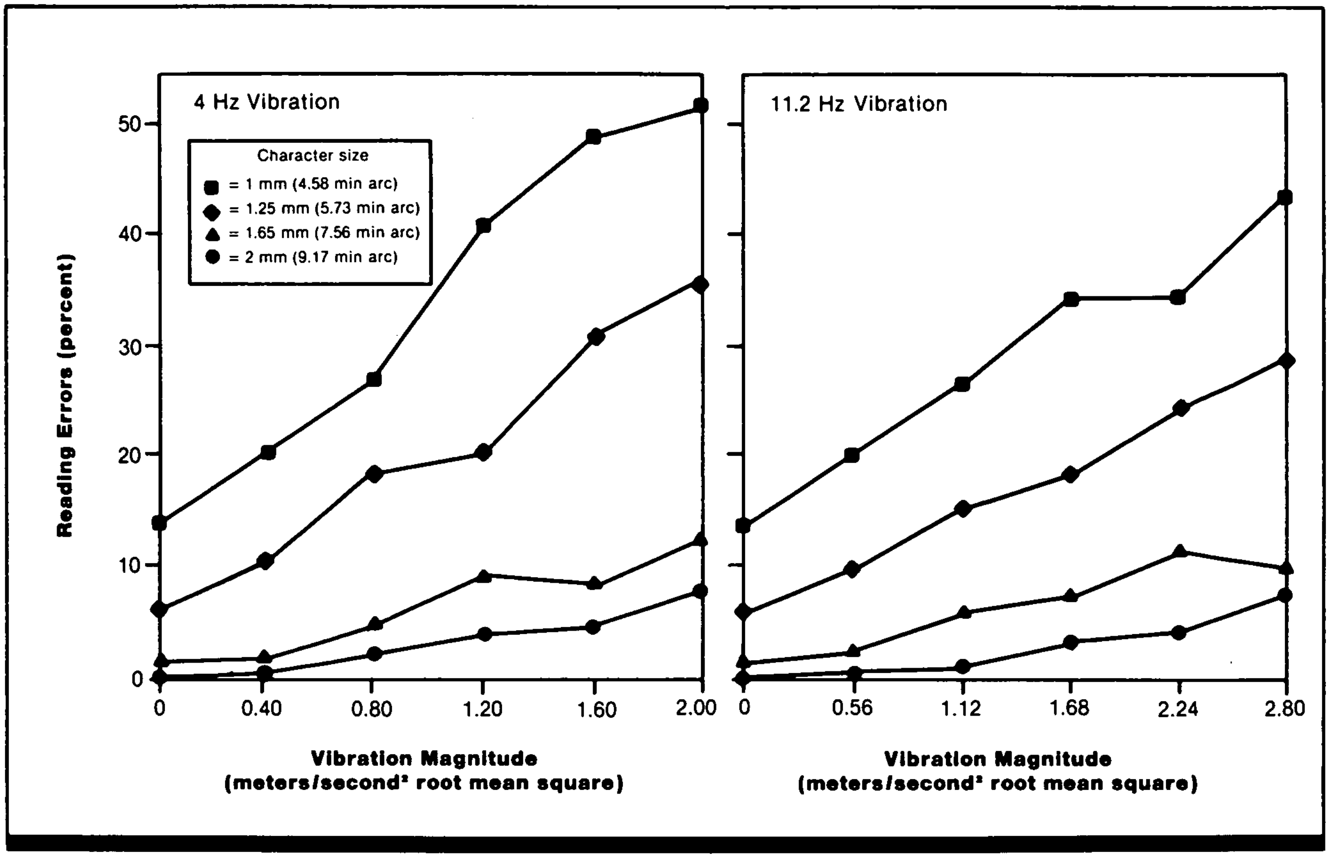


Figure 1. Increase in mean reading error with vibration magnitude for four character sizes. (From Ref. 1)

Key Terms

Alphanumeric displays; display vibration; head-down displays; legibility; panel-mounted displays; reading error; whole-body vibration

General Description

Substantial legibility loss occurs when display symbols subtending a suboptimal character height are viewed in a vibration environment.

Applications

Panel-mounted **head-down displays** with alphanumeric content situated in environments subject to vibration.

Methods

Test Conditions

- 5 x 10 array of 50 light numerals, five of each numeral, randomly arranged; numerals, on a dark background, on mono-chrome video monitor; symbol luminance = 7 cd/m^2 with luminance contrast >90%, viewing distance = 0.75 m and character subtense from 4.58-9.17 min arc of visual angle
- Vibration stimulus presented vertically (z-axis) to observers seated on a hard flat seat without backrest; binocular viewing
- Vibration frequency range 4-11.2 Hz; vibration magnitude between 0 and 2.8 m/sec^2 root mean square (rms)

Experimental Procedure

- Repeated measures design
- Independent variables: vibration frequency, vibration magnitude, character subtense
- Dependent variable: reading error
- Observer's task: paced reading at one character/sec
- 10 observers, college students and staff, some practice

Experimental Results

- Mean data indicate a significant linear trend, with reading errors increasing with increased vibration magnitude for all but the largest subtense.
- At higher vibration magnitudes, substantial errors (8.2% at 4 Hz and 8.0% at 11.2 Hz) occur, even at the largest character subtense (9.17 min arc of visual angle).

Variability

Standard deviations for each experimental condition show great individual variability.

Repeatability/Comparison with Other Studies

Other studies show similar large decrements in display legibility when small (<10 min arc of visual angle) characters are viewed within a vibration environment.

Constraints

- The extent of display degradation is dependent not only on the character subtense but on the nature of the vibration stimulus (CRef. 10.411) and other display parameters.

Key References

*1. Lewis, C. H., & Griffin, M. J. (1979). The effect of character size on the legibility of a numeric display during vertical whole-body vibration. *Journal of Sound and Vibration, 67*, 562-565.

Cross References

10.409 Factors affecting human performance during vibration;

10.411 Display legibility: effects of vibration frequency;

10.414 Display legibility during vibration: effect of character spacing;

11.115 Dot matrix displays: effect of inter-pixel spacing on character identification;

11.209 Alphanumeric font and display legibility

10.414 Display Legibility During Vibration: Effect of Character Spacing

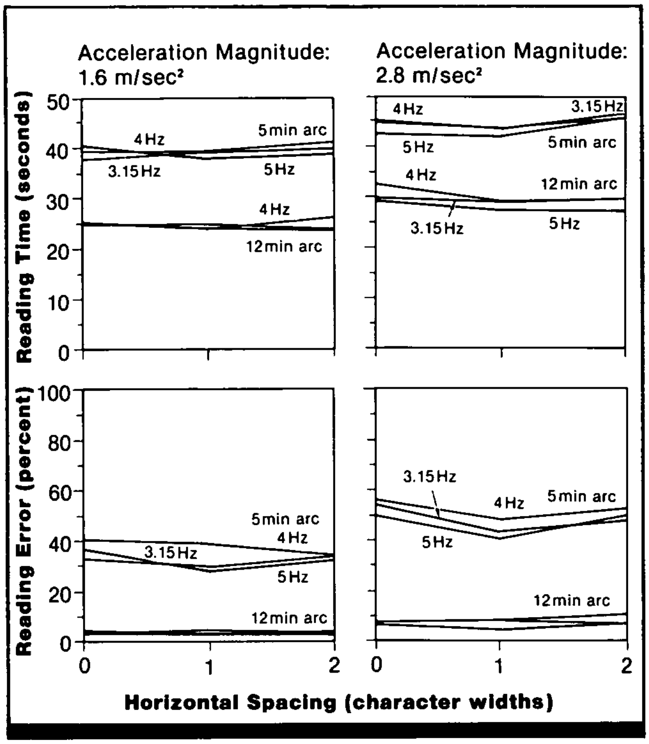


Figure 1. Reading time and reading error as functions of horizontal character separation.

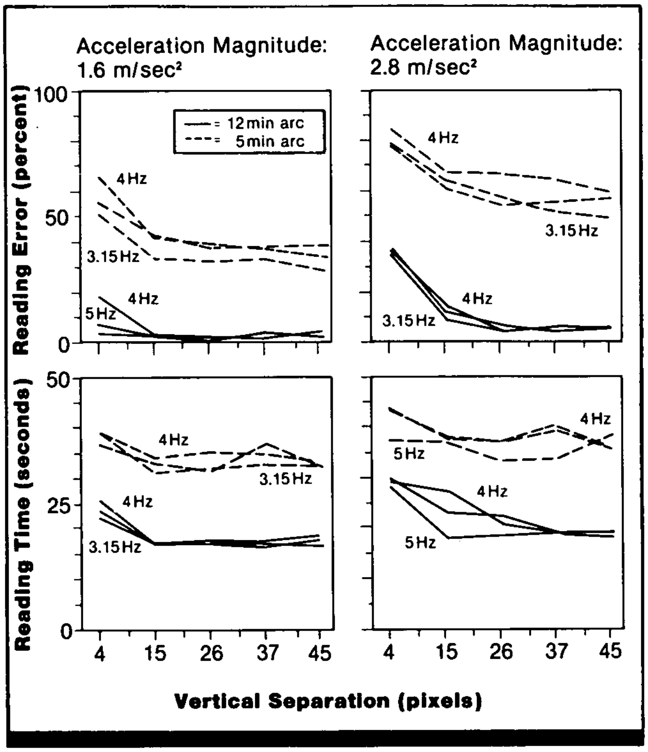


Figure 2. Reading time and reading error as functions of vertical character separation.

Key Terms

Alphanumeric displays; display vibration; head-down displays; legibility; panel-mounted displays; reading error; whole-body vibration

General Description

With small-subtense characters, horizontal character separation of one character width optimizes a display's legibility during vertical whole-body vibration. Substantial loss of display legibility occurs with inadequate vertical separation between characters on a display during vertical vibration.

Applications

Panel-mounted **head-down displays** with an alpha-numeric content in environments subject to vibration, e.g., fixed and rotary wing aircraft.

Methods

Test Conditions

- 3 x 10 array of 30 numerals (Fig. 1) and 5 x 10 array of 50 light numerals (Fig. 2), on a dark background on a monochrome video monitor; symbol definition = 5 x 7 circular pixels within an 8 x 11 cell, symbol luminance = 7 cd/m^2 with luminance contrast >90%, character subtense = 5 and 12 min arc of visual angle, horizontal character separation range 0-2 character widths and vertical separation 4-45 pixels
- Vibration stimulus presented vertically (z-axis) to observers seated on a hard flat seat without backrest; binocular viewing; viewing distance = 0.75 m
- Vibration frequency 3.15, 4, 5 Hz, and **acceleration magnitude** 1.6-2.8 m/sec^2 rms

Experimental Procedure

- Independent variables: vibration frequency, acceleration magnitude, horizontal character separation, vertical character separation
- Dependent variables: reading errors, reading time
- Observer's task: read numbers as fast and as accurately as possible
- College students and staff, with some practice, as observers

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Only with the finest resolution visual task (5 min arc of visual angle) viewed during severe [2.8 m/sec^2 root mean square (rms)] whole-body vibration is there any significant effect of horizontal character separation.
- A horizontal character separation of one character width will optimize legibility when small subtense, row-formatted symbology is viewed during severe vibration conditions.
- Horizontal character separation should not normally influence legibility of display symbols presented at realistic subtenses during whole-body vertical vibration.
- At an acceleration magnitude of 1.6 m/sec^2 rms, an increase of up to 35% reading error and up to 10 sec in reading time occurs with a reduction in vertical spacing from 15-4 pixels; at an acceleration magnitude of 2.8 m/sec^2 rms, up to 26 pixel separation is required to reduce performance decrements similar to those with the 1.6 m/sec^2 rms vibration stimulus.

Variability

No information about variability was given.

Repeatability/Comparison with Other Studies

Reference 1 draws similar conclusions with respect to horizontal separation and legibility during whole-body vibration.

Constraints

- The extent of display degradation is dependent not only on spatial separation of symbols but on the nature of the vibration stimulus (CRefs. 10.411, 10.412) and other parameters of the display (CRefs. 10.411, 10.415, 10.416).

Key References

1. Crook, M. N., Harker, G. S., Hoffman, A. C., & Kennedy, J. L. (1948). *Studies of the effect of typographical spacing on the legibility of numerals under vibration* (Tech. Memo MCR EXC-69410). Aero Medical Laboratory, Wright Field, Dayton, OH (DTIC No. ADA950047)

*2. Moseley, M. J., & Griffin, M. J. (1986). Effects of display vibration and whole body vibration on visual performance. *Ergonomics, 29*, 977-983.

Cross References

10.409 Factors affecting human performance during vibration;

10.411 Display legibility: effects of vibration frequency;

10.412 Visual performance: effect of random multiple-frequency and multiple-axis vibration;

10.413 Display legibility during vibration: effect of character subtense;

10.415 Display legibility during vibration: effect of character font during whole-body vibration;

10.416 Display legibility during vibration: effect of luminance contrast;

10.435 Spatial filtering descriptions of vibration-induced visual disruption;

11.209 Alphanumeric font and display legibility

10.415 Display Legibility During Vibration: Effect of Character Font During Whole-Body Vibration

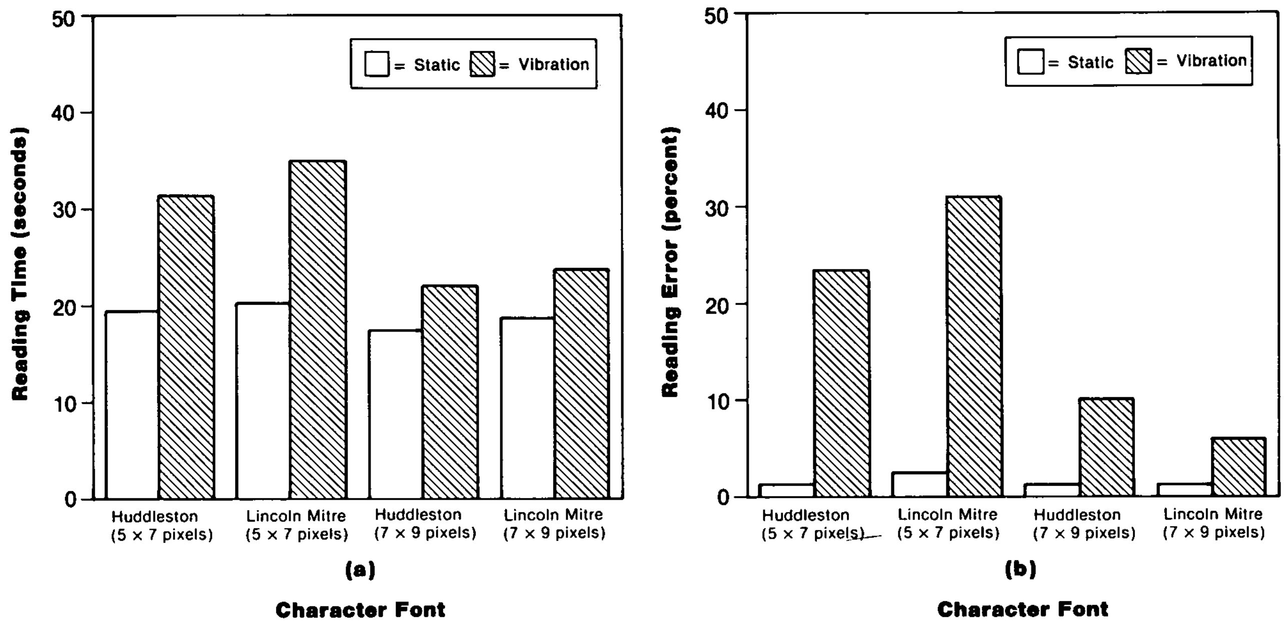


Figure 1. Effect of character font on (a) reading time and (b) reading error during whole-body vibration. (From Ref. 2)

Key Terms

Display vibration; fonts; Huddleston font; legibility; Lincoln Mitre font; reading error; whole-body vibration

General Description

A symbol defined with a larger number of pixels is read more quickly, under both static and vibration-degraded conditions. Huddleston and Lincoln Mitre fonts are read equally fast regardless of vibration and pixel variation. Reading errors are fewer with greater pixel definition only under vibration conditions. Both fonts produce similar error rates with the better-defined pixel condition; with fewer pixels, the Huddleston font produces fewer errors.

Methods

Test Conditions

- Two horizontal lines of nine light alphanumeric characters with four-character height vertical separation, presented on a dark background on a monochrome video monitor; 7 cd/m^2 symbol luminance contrast > 90%; 12 min arc angular subtense of all characters; character fonts: Huddleston and Lincoln Mitre; dot matrix symbol definition: 5 x 7 and 7 x 9 pixels; vibration: 0 and 4 Hz (2.8 m/sec^2 root mean square acceleration magnitude)
- Vibration stimulus presented vertically (*z*-axis) to observers seated on hard flat seat without backrest
- Binocular viewing at 0.63-m viewing distance

Experimental Procedure

- Repeated measures design
- Independent variables: vibration, character font, symbol definition
- Dependent variables: reading error, reading time
- Observer's task: read display of 18 characters as fast and as accurately as possible
- 8 observers, college students and staff, practice given until error-free performance obtained in unpaced static trial

Experimental Results

- Mean data indicate that during vibration, a 7 x 9 pixel symbol is read more quickly and accurately than is a 5 x 7 pixel symbol. Under the static condition the 7 x 9 pixel symbol is again read more quickly ($p < 0.05$).
- There is no difference in reading speed between 7 x 9 Huddleston and 7 x 9 Lincoln Mitre fonts during static and vibration conditions.
- There is no difference in reading speed and accuracy between Lincoln Mitre and Huddleston fonts at 5 x 7 or 7 x 9 symbol definition conditions during static conditions.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

• Huddleston font produces fewer errors than Lincoln Mitre font at 5 x 7 symbol definition in terms of reading error during vibration ($p < 0.05$).

Variability

No significant observer variation over four repetitions of the visual task per font per symbol definition combination.

Repeatability/Comparison with Other Studies

Other studies (Ref. 1) have shown a small increase in legibility when symbol definition increases from 5 x 7 to 7 x 9 during display vibration. Similar results for static data have been reported (Ref. 3).

Key References

1. Meddick, R. D. L. (1977). *The legibility of two-axis vibrated test material when presented to stationary seated observers.* Unpublished master's thesis, University of Southampton, Southampton, England.

*2. Moseley, M. J. (1982, September). *The legibility of dot matrix characters viewed under conditions of whole-body vibration.* Paper presented at the U. K. Informal Group Meeting on Human Response to Vibration-Health and Safety Executive, Cricklewood, London.

3. Moseley, M. J. & Griffin, M. J. (1986). *A design guide for visual displays and manual control in vibration environments. Part I, Visual displays* (ISOR-TR-133). The University of Southampton: Southampton, England.

4. Shurtleff, D. A. (1980). *How to make displays legible.* La Mirada, CA: Human Interface Design.

Cross References

10.409 Factors affecting human performance during vibration

10.416 Display Legibility During Vibration: Effect of Luminance Contrast

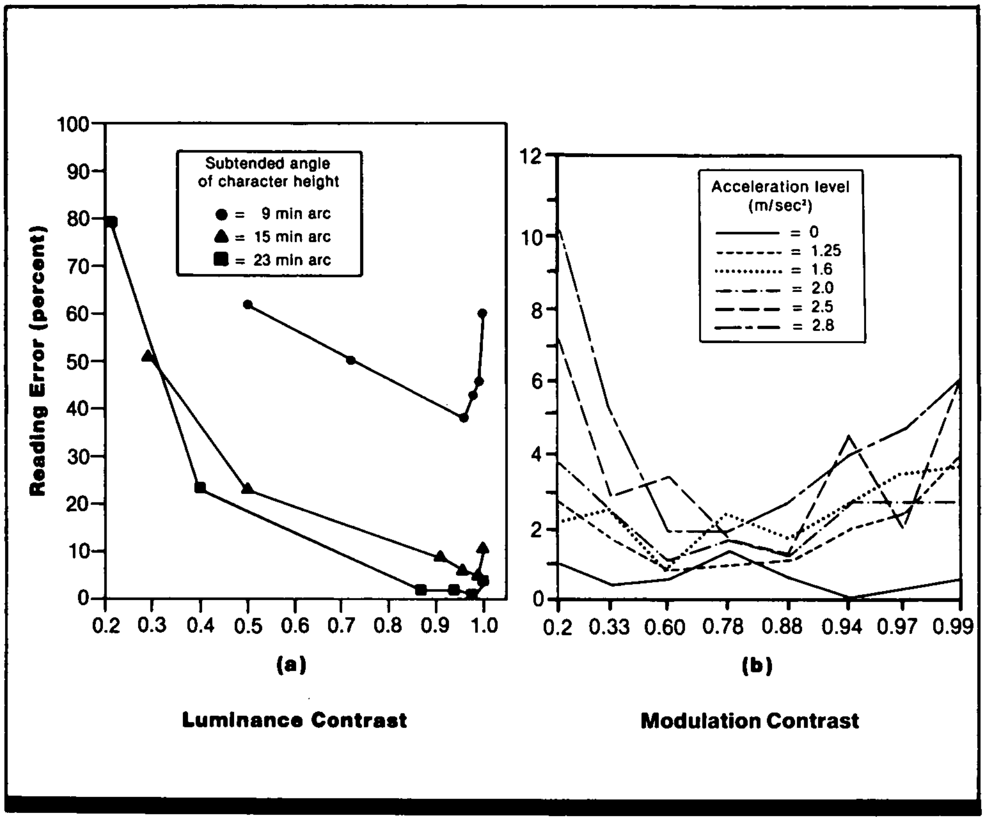


Figure 1. Effect of luminance contrast on reading errors with (a) helmet-mounted displays (Ref. 1) and (b) panel-mounted displays (Ref. 2.). Note that calculation of contrast (and scale of horizontal axis) is different for panels (a) and (b) (see Methods section).

Key Terms

Contrast; display vibration; head-down displays; helmet-mounted displays; legibility; panel-mounted displays; reading error; whole-body vibration

General Description

Under conditions of vibration, for both helmet-mounted displays and panel-mounted head-down displays, display legibility increases as luminance contrast increases for low and moderate contrast levels. Very high values of luminance contrast may degrade the legibility of displays viewed in a vibration environment.

Methods

Test Conditions

- Single horizontal line of five randomly selected numerals defined by 5 x 7 circular pixels, internally generated symbol luminances of 48.3, 19.2, 12.7 cd/m^2 (Fig. 1a), and 27.41 cd/m^2 (Fig. 1b); background luminances of 48.0, 19.2, 1.9, 0.9, 0.2, 0.0 cd/m^2 (Fig. 1a); luminance contrast from 0.21-1.0, with contrast calculated as $C = L_{target}/(L_{target+background})$ (Fig. 1a) and from 0.20-0.99, with contrast calculated as Michelson contrast (modulation contrast), i.e., $C = (L_{max} - L_{min})/(L_{max} + L_{min})$ (Fig. 1b)
- Vibration frequency of 4 Hz; acceleration magnitude of 1 m/sec^2 root mean square (rms) (Fig. 1a), and between 0-2.8 m/sec^2 rms (Fig. 1b)
- Vibration presented vertically (z-axis) to observer seated on hard flat seat, with backrest (Fig. 1a), and without backrest (Fig. 1b); binocular viewing

Experimental Procedure

- Repeated measures design
- Independent variables: luminance contrast, character subtense (Fig. 1a); luminance contrast, acceleration magnitude (Fig. 1b)
- Dependent variable: reading errors
- Observer's task: paced reading at one character per sec (Fig. 1a); observers instructed to read as fast and as accurately as possible (Fig. 1b)
- 10 observers (Fig. 1a); 8 observers (Fig. 1b), college students and staff, some practice

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Mean data indicate a significant quadratic trend of reading errors with background luminance ($p<0.001$) (Ref. 1).
- Error rate decreases as target-background contrast increases except at the highest contrast levels. The decline in symbol legibility at high contrast is especially pronounced for small (9 min arc) symbols (Fig. 1a).
- Increase in reading errors at high levels of luminance contrast is proportional to acceleration magnitude of the vibration stimulus (Fig. 1b).

Variability

Standard deviation of error score for individual conditions is provided in Ref. 1 (Fig. 1a). No other dispersion measures are provided.

Repeatability/Comparison with Other Studies

Reference 3 identifies a similar loss of legibility from excessive display contrast during in-flight vibration trials with a helmet-mounted display.

Constraints

- The extent of display degradation depends not only on the luminance contrast of the display, but also on the vibration stimulus (CRef. 10.411) and other parameters of the display (CRefs. 10.413, 10.414, 10.416).

Key References

*1. Furness, T. A. (1981). *The effects of whole-body vibration on the perception of the helmet-mounted display*. Unpublished doctoral dissertation, University of Southampton, England.

*2. Moseley, M. J. (1983, September). *The effect of contrast variation on the legibility of a display during observer whole-body vibration*. Paper presented at the U.K. Informal Meeting on Human Response to Vibration; National Institute of Agricultural Engineering (NIAE), Silsoe, Berkshire, England.

Cross References

10.409 Factors affecting human performance during vibration;

10.411 Display legibility: effects of vibration frequency;

10.413 Display legibility during vibration: effect of character subtense;

10.414 Display legibility during vibration: effect of character spacing;

10.416 Display legibility during vibration: effect of luminance contrast

10.417 Visual Performance During Whole-Body Vibration: Effects of Viewing Distance and Display Collimation

Key Terms

Display collimation; display vibration; eye movements; eye rotation; legibility; reading; tracking

General Description

The effect on visual performance of varying the viewing distance during whole-body vibration depends on the axis of induced eye motion (CRefs. 10.407, 10.418). Retinal image displacement is responsible for the vibration-induced visual performance decrement. For translational eye motion, the amplitude of retinal image displacement is inversely proportional to the viewing distance. Increasing the viewing distance (or using a collimated display image to put the image at infinity) decreases vibration-induced image motion. If eye motion is rotational, varying the viewing distance will not affect the amplitude of image motion. Irrespective of the axis of eye motion, decreasing the viewing distance increases the retinal image size. When rotational eye motion is dominant, decreased viewing distance improves visual performance by increasing the size of the retinal image without significantly increasing retinal image motion (CRef. 10.413).

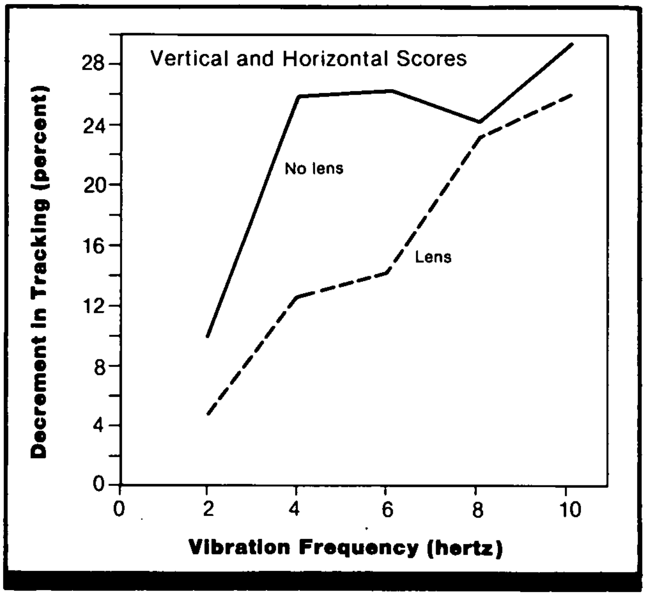


Figure 1. Performance decrement on tracking task during whole-body vibration with collimated (lens) and uncollimated (no lens) displays. (From Ref. 3)

Applications

Display collimation may reduce decrements in visual performance caused by relative translational vibration between the observer and the display. When the relative motion is rotational, performance decrements may be reduced by decreasing the viewing distance.

Methods

Test Conditions

- Lens conditions: display mounted 734 mm in front of observer (no lens condition) or 988 mm in front of observer with a lens mounted at its focal length in front of the display to collimate it (lens condition)
- Discrete sinusoidal vibration frequencies of 2, 4, 6, 8 and 10 Hz
- Observer wore no restraint or wore combined parachute and restraint harness
- Vertical (*z*-axis) whole-body vibration via an electro-mechanical vibrator, constant peak-to-peak displacement of 6.5mm
- Compensatory (zero-reader) tracking display mounted at eye level; display cross luminance of 1.88 cd/m^2; operated with two-axis joystick on right side of seat
- Collimating lens: biconvex, 734 mm focal length
- Observer sat on unpadded ejection seat; wore flight helmet and overalls

Experimental Procedure

- Incomplete factorial design based on lens condition, vibration frequency, restraint condition; each observer performed five runs per lens condition; there were four runs per lens condition per frequency x restraint condition
- Independent variables: vibration frequency, restraint condition, lens condition
- Dependent variables: vertical, horizontal, combined vertical and horizontal time-on-target
- Time-on-target data: $[p(\text{before}) + p(\text{after})/2] - p(\text{vibration})$ where: p(before) = percentage time-on-target score during 5-min period before vibration, p(after) = percentage time-on-target score during 5-min period after vibration, p(vibration) = percentage time-on-target score during 5 min of vibration
- Observer's task: nullify inputs by maintaining a moving cross wire in the center of a stationary circle using a two-axis joystick
- 8 observers, staff members

Experimental Results

- Collimation produces a significant improvement in performance ($p < 0.01$) at 4 and 6 Hz. As vibration frequency increases, combined horizontal and vertical time-on-target decreases ($p < 0.001$).

Variability

Mann-Whitney test after analysis of variance shows collimation effect. Analysis of variance shows no significant effect of restraint on any dependent variable; no effect of vibration frequency, restraint, or lens condition on vertical or horizontal time-on-target.

Repeatability/Comparison with Other Studies

In the 7-60 Hz range, the minimum amplitudes of *z*-axis whole-body vibration which cause image blur result in predominantly rotational eye motion at normal viewing distances (Ref. 1). Collimation will therefore not normally be beneficial at frequencies greater than 27 Hz.

The data apply to unrestrained head motion induced by *z*-axis vertical seat vibration; different seating conditions (e.g., reclining or semi-reclining seats) or axes of vibrational input may change the relative amplitudes of rotational and translational vibration to the head and eyes.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Griffin, M. J. (1976). Eye motion during whole-body vertical vibration. *Human Factors, 18*, 601-606.

2. McLeod, R. W., & Griffin, M. J. (1983). *Whole-body vibration and aircrew performance* (ISVR Progress Report 24/19, MOD Research Agreement 2040/0180). Southampton, England: University of Southampton, Institute of Sound and Vibration Research.

*3. Wilson, R. V. (1974). Display collimation under whole-body vibration. *Human Factors, 16*, 186-195.

Cross References

9.527 Inherently unstable dynamics: the critical tracking task;

10.407 Transmission of vertical seat vibration to the head;

10.413 Display legibility during vibration: effect of character subtense;

10.418 Transmission of vibration to the eyes

10.418 Transmission of Vibration to the Eyes

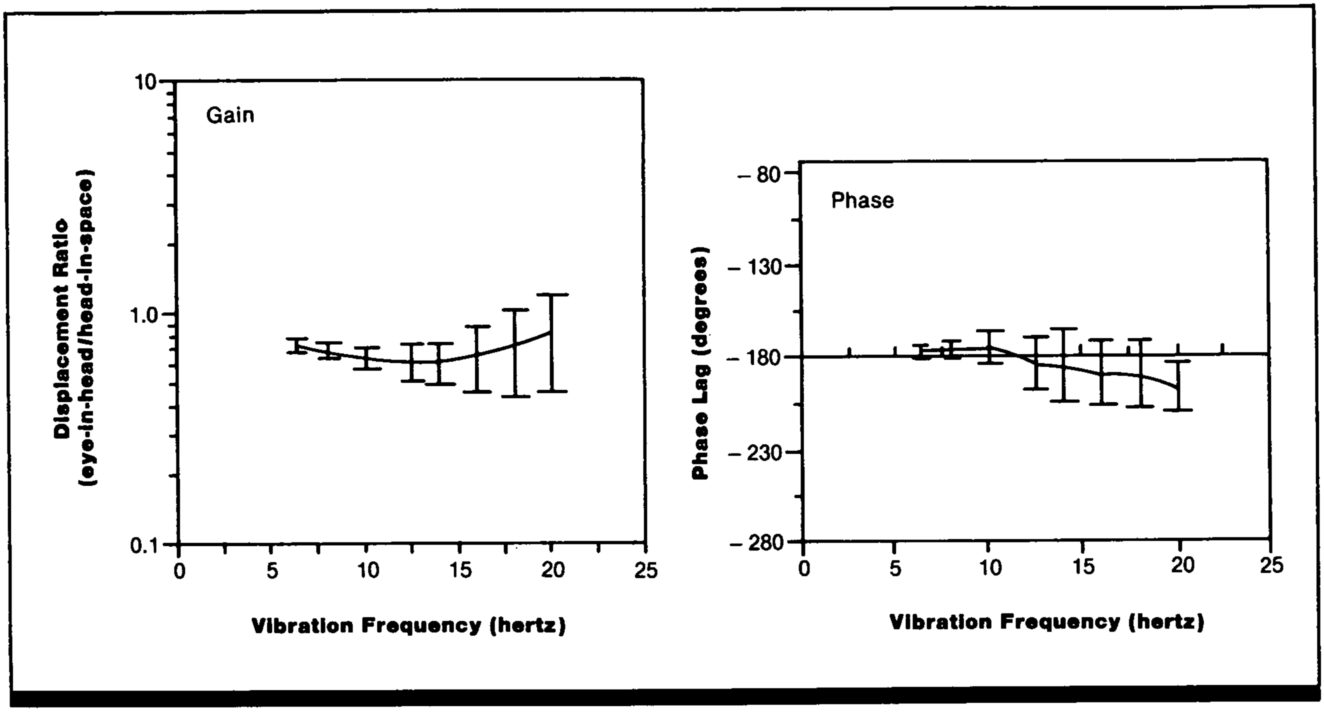


Figure 1. Gain (a) and phase (b) of head-to-eye transfer function with pitch-axis head vibration. (From Ref. 9)

Key Terms

Compensatory eye movements; eye-head coordination; head rotation; head vibration; rotational eye movements; vestibulo-ocular reflex

General Description

Transmission of vibration to the eyes depends on the axis and frequency of head vibration occurring in any or all of the six axes of motion (CRef 10.407). During pitch and yaw axis head vibration, at frequencies <5 Hz, the activity of the **vestibulo-ocular reflex** stabilizes the eyes in space by producing eye rotation equal and opposite to head rotation. A similar compensatory reflex may occur for roll-axis head rotation, but with insufficient eye rotation to produce effective stabilization (Ref. 4). Rigidity of the eye-in-head coupling in the three translational axes means that translational eye vibration is nearly the same as head vibration at frequencies up to 20 Hz. Displacement of the center-of-gravity of the eye from its center of rotation means that head translation may induce eye rotation (Ref. 5). Minimum amplitudes of *z*-axis whole-body vibration which result in visual blur produce predominantly rotational eye motion (Ref. 2). The data describe the modulus and phase of the transfer function of pitch-axis eye motion resulting from pitch-axis head rotation at frequencies between 6.3 and 20 Hz.

Applications

Measuring small displacement eye movements in other than laboratory environments is difficult. The head-to-eye vibration transfer function predicts vibration-induced eye motion (and the concomitant decrement in visual performance) from a measure of head vibration.

Methods

Test Conditions

- Discrete sinusoidal vibration of 6.3-20 Hz; each frequency presented three times in random order
- Pitch-axis vibration, 12 deg/sec peak, via bite-bar attached to an electromagnetic vibrator producing vibration around **atlanto-occipital** joint
- Visual target: 8 horizontal lines; height: 2 min arc of visual angle; separation: 9.3 min arc; width: 16 deg; on oscilloscope; viewed at optical infinity through a plano-convex lens (153 mm diameter, 340 mm focal length) one focal length from display
- Patch worn over left eye; darkened chamber

Experimental Procedure

- Independent variable: vibration frequency
- Dependent variables: amplitude and phase of target oscillation (relative to head oscillation); eye-in-head vibration amplitude (*Eh*) and phase (α) derived by vector subtraction:

$Eh =$
$(Es^2 + Hs^2 - 2Es \cdot Hs \cdot \cos \sigma)^{1/2}$

$\alpha =$
$\arctan [\sin \sigma / (\cos \sigma - Hs/Es)]$

where σ = phase between displacement of eye-in-space (*Es*) (derived from target displacement) and head-in-space (*Hs*)

- Observer's task: adjust the amplitude and phase of visual target oscillation until the lines appeared stationary
- 8 male observers with at least 20/20 vision in right eyes

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Mean eye-in-space displacement is less than head-in-space displacement at all frequencies: mean peak-to-peak eye displacement is 4.1 min arc of visual angle at 6.3 Hz, 5.8 min arc at 20 Hz; head displacement is 36.1 min arc at 6.3 Hz, 11.5 min arc at 20 Hz.
- Mean modulus of the head-to-eye transfer function is 0.78-0.87 at frequencies <10 Hz; the mean modulus decreases to a minimum of 0.74 at 14 Hz and increases to 1 at 20 Hz.
- Mean phase lag of the transfer function increases with increasing frequency from approximately 180 deg at 6.3-10 Hz to 197 deg at 20 Hz.

Variability

Error bars in Fig. 1 indicate ± 1 standard deviation. Three-way analysis of variance (observers x repetitions x frequencies) shows a significant ($p<0.01$) effect of observers and frequency (phase) and observers (modulus).

Repeatability/Comparison with Other Studies

Figure 2 compares data from the present experiment with data from four previous experiments which investigated the frequency range between 0.005 and 100 Hz.

Constraints

- Head rotation produces eye translation and rotation; therefore eye stabilization for rotational head motion may still result in retinal image motion of nearby objects (CRef. 10.417).
- Small differences from a modulus of 1 and phase lag of 180 deg may affect amplitude of eye-in-space motion (Ref. 8).

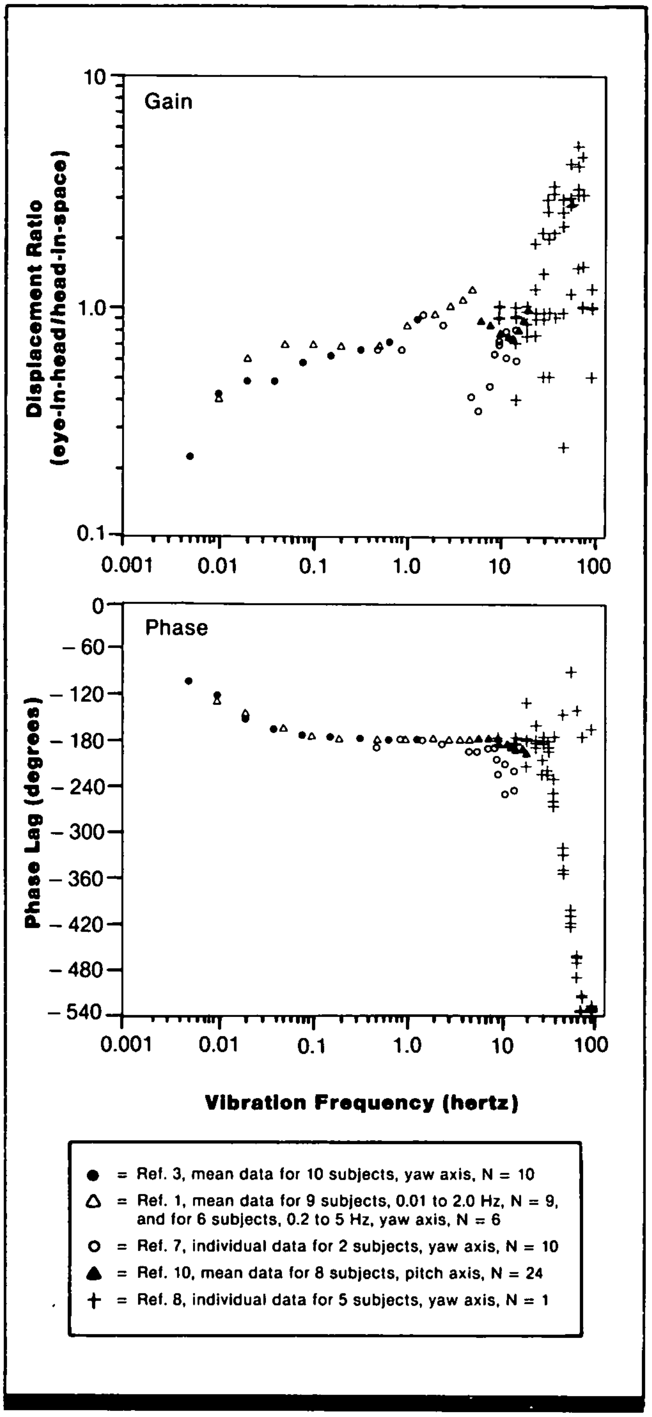


Figure 2. Results of five investigations of pitch or yaw axis rotational eye motion resulting from pitch or yaw head motion.

Key References

1. Benson, A. J. (1970). Interaction between semicircular canals and gravireceptors. In D. E. Busby (Ed.), *Recent advances in aerospace medicine* (pp. 249-261). Dordrecht, Netherlands: D. Reidel Publishers.

2. Griffin, M. J. (1970). Eye motion during whole-body vertical vibration. *Human Factors, 18*, 601-606.

3. Hixson, W. C. (1974). *Frequency response of the oculo-vestibular system during yaw oscillation.* (NAMRL-1212). Pensacola, FL: Naval Aerospace Medical Research Laboratory. (DTIC No. ADA009769)

4. Jones, M. G., Barry, W., & Kowalsky, N. (1964). Dynamics of the semicircular canals compared in yaw, pitch, and roll. *Aerospace Medicine, 35*, 984-989.

5. Nickerson, J. L., Paradijeff, A., & Feinhandler, H. S. (1963). *Study of the effects of externally applied sinusoidal forces on the eye* (AMRL-TDR-63-120). Wright-Patterson Air Force Base, OH.

6. Parks, R. S., & Parks, G. E. (1933). The center of ocular rotation in the horizontal plane. *American Journal of Physiology V, 104*, 545-552.

7. Skavenski, A. A., Hansen, R. M., Steinman, R. M., & Winterson, B. J. (1979). Quality of retinal image stabilization during small natural and artificial body rotations in man. *Vision Research, 19*, 675-683.

8. Stott, J. R. R. (1982, September). *The ocular response to yaw axis head vibration.* Paper presented to the U. K. Informal Group Meeting on Human Response to Vibration. Health and Safety Executive, Cricklewood, London.

*9. Wells, M. J. (1983). *Vibration-induced eye movements and reading performance with the helmet-mounted display.* Unpublished doctoral dissertation, University of Southampton, England.

*10. Wells, M. J., & Griffin, M. J. (1983). *Vibration-induced eye motion.* Paper presented at the 54th Annual Scientific Meeting of the Aerospace Medical Association, Houston, TX.

Cross References

1.917 Factors affecting the vestibulo-ocular reflex;

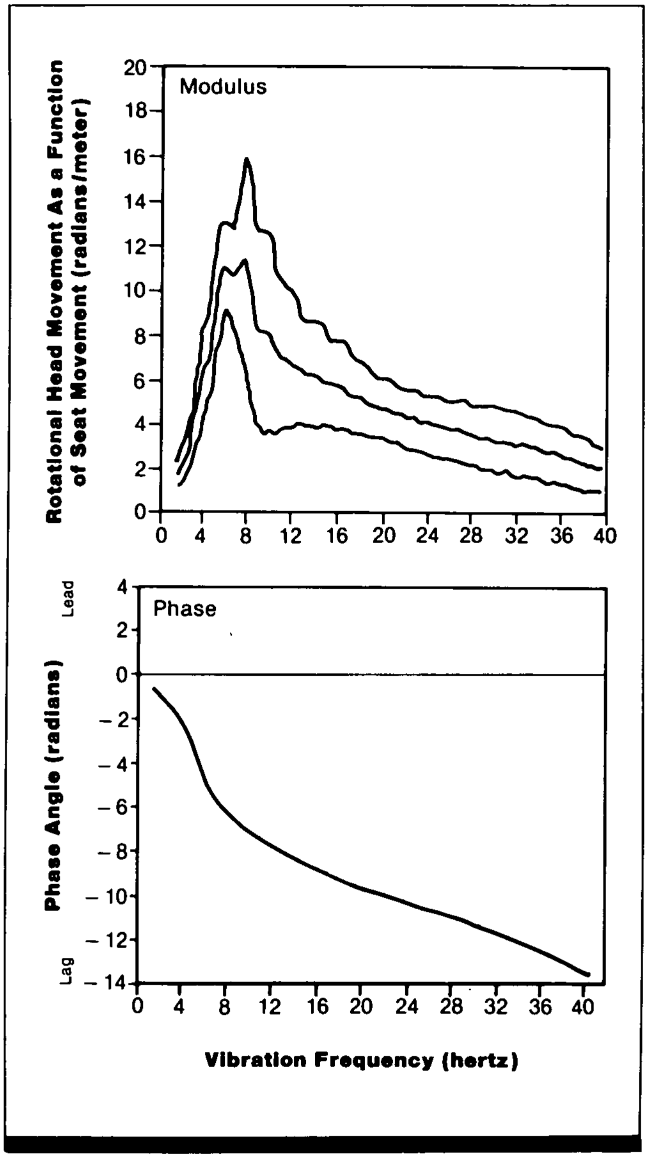
1.918 Factors influencing visual suppression of vestibular nystagmus;

10.406 Factors affecting vibration transmission through the body;

10.407 Transmission of vertical seat vibration to the head;

10.417 Visual performance during whole-body vibration: effects of viewing distance and display collimation

10.419 Transmission of Vibration to Helmets



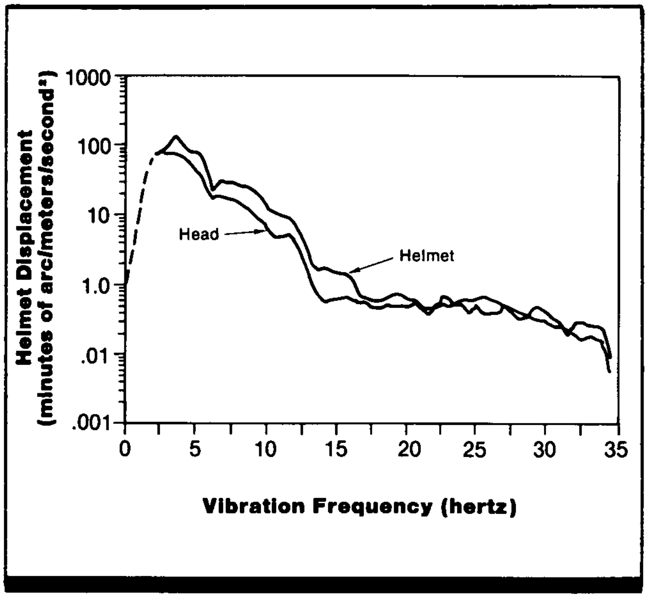


Figure 1. Modulus and phase of rotational head movement as a function of seat movement. Middle curve shows mean values; upper and lower curves show ±1 standard deviation from the mean. (From Ref. 1)

Figure 2. Helmet displacement as a function of vibration frequency. (From Ref. 2)

Key Terms

Display vibration; head vibration; helmet-mounted displays; helmets; vibration transfer functions; whole-body vibration

General Description

The transmission of whole-body vibration to the helmet is determined largely by axis, amplitude, and frequency of head vibration. Factors influencing head vibration (e.g., subject's posture; seating configuration; head-pointing angle; vibration frequency, axis, and amplitude) also affect helmet vibration (CRef. 10.407). Head-to-helmet coupling (helmet fit) and helmet loading affect the way vibration is transmitted from the head. The added mass of a helmet may significantly alter the transmission of whole-body vibration to the head. Of the six axes of helmet vibration which may result from vertical (*z*-axis) whole-body vibration, the amplitudes on the axes of pitch and yaw are sufficient to affect performance with collimated helmet-mounted sights or displays (CRef. 10.420).

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Vertical vibration: z-axis whole-body vibration applied to seated subject through a hard (unpadded) simulated helicopter seat; subject restrained with a five-point harness
- Swept sine vibration input, 0-60 Hz in 100 sec generated by electrodynamic vibrator at 1 m/sec^2 root mean square; seat acceleration measured with a piezo-resistive translational accelerometer under the seat. Helmet acceleration measured with rotational servo accelerometer on top of the helmet
- Multiple axis in-flight vibration: Sea King helicopter flying at 93 km/hr at 31 m altitude; subject seated in the front left seat restrained with a five-point harness; 60-sec time histories recorded; z-axis seat acceleration measured with piezo-resistive translational accelerometer mounted in a SAE PAD between the subject and the seat; pitch axis helmet and head acceleration measured with rotational servo accelerometers on top of helmet or on bite-bar

Experimental Procedure

- Independent variables: for vertical vibration—vibration frequency; for multiple axis in-flight vibration—7 flight conditions (data from one condition shown)
- Dependent variables: seat, head, helmet vibration
- Subject's task: for vertical vibration—to maintain a relaxed but erect posture; for multiple axis in-flight vibration—to look straight ahead, make a minimum of voluntary head movements, and maintain same posture used when flying aircraft.
- 11 subjects: 10 male research workers, 1 male test pilot

Experimental Results

- For vertical vibration-transfer functions (Fig. 1) derived using cross-spectral analysis of acceleration time histories,

$$H(f) = Sxy(f)/Sxx(f) \quad (1)$$

where $Sxy(f)$ = cross spectrum of input and output, $Sxx(f)$ = power spectrum of input, $H(f)$ = transfer function. Peaks in the moduli occur for all subjects between 6 and 8 Hz at a mean amplitude of ~11 rad/sec^2 per m/sec^2; beyond 16 Hz moduli decreases to 2 rad/sec^2 per m/sec^2 at 40 Hz.
- For multiple axis in-flight vibration, acceleration time histories were high-pass filtered (digital filter, 2 Hz, 12 dB/octave); head and helmet acceleration time histories double integrated to yield displacement. Transfer function derived using total power at seat, head, and helmet:

$$|H(f)| = [Syy(f)/Sxx(f)]^{1/2} \quad (2)$$

where $Syy(f)$ = power spectrum of output, $Sxx(f)$ = power spectrum of input, $|H(f)|$ = transfer function modulus. Helmet displacement decreases with increasing frequency from >100 min arc of visual angle per m/sec^2 at 3.5 Hz to <1 min arc per m/sec^2 at 17.5 Hz.

Variability

Vertical vibration: Fig. 1 shows ± 1 standard deviation, reflecting the variability between subjects.

Repeatability/Comparison with Other Studies

Investigations of transfer of whole-body vibration to helmet produced results similar to those shown in Fig. 2 (Ref. 2). In-flight measurement (in the same helicopter) of helmet and helmet mounted display vibration during 130 km/hr forward flight, showed pitch axis displacement of >50 min arc per m/sec^2 seat acceleration at 3.5 Hz (Ref. 1); this may reflect ability of different subjects to minimize transmission of vibration to the head.

Constraints

- There is evidence of a non-linear effect of vibration amplitude on the transfer function (Ref. 1).
- The transfer function derived from single-axis vibration cannot adequately predict amplitude of helmet vibration during multiple axis in-flight vibration.
- In-flight vibration: subjects differ significantly in their ability to isolate head and helmet from in-flight vibration (Ref. 2).
- Changing head-helmet coupling (e.g., wearing an oxygen mask) may change transfer of vibration to helmet.

Key References

*1. Furness, T. A. (1981). *The effects of whole-body vibration on the perception of the helmet-mounted display*. Unpublished doctoral dissertation, University of Southampton, England.

*2. Wells, M. J. (1983). *Vibration-induced eye movements and reading performance with the helmet-mounted display*. Unpublished doctoral dissertation, University of Southampton, England.

Cross References

10.406 Factors affecting vibration transmission through the body;

10.407 Transmission of vertical seat vibration to the head;

10.420 Perception of information on helmet-mounted displays during vibration

10.420 Perception of Information on Helmet-Mounted Displays During Vibration

Key Terms

Display vibration; head-coupled systems; helmet-mounted displays; helmets; image stabilization; reading; stabilization; whole-body vibration

General Description

Helmet-mounted display (HMD) reading performance is severely degraded during whole-body vertical vibration at frequencies <10 Hz. Performance loss is the result of rotational vibration of the head (CRef. 10.407) and the helmet (CRef. 10.419) which causes relative motion between the eye and the display. The **vestibulo-ocular reflex** space stabilizes the eyes during rotational head vibration (CRef. 10.418). Image stabilization from deflecting the image on the display to match the eye's line of sight can significantly reduce vibration-induced performance loss.

Methods

Test Conditions

- Vertical (z-axis) whole-body vibration applied to seated observer through a hard (unpadded) simulated helicopter seat mounted on an electro-dynamic vibrator; discrete sinusoidal vibration at the eleven 1/3-octave preferred center frequencies at 2.5-25 Hz, at 53% of the ISO 1-min **fatigue-decreased proficiency boundary**
- 50 numerals in a 10 x 5 array; five of each numeral from 0-9, randomly arranged; **Huddleston font,** 7 x 5 dot matrix
- Numeral height: 15 min arc of visual angle; width: 10.7 min arc; horizontal separation: 20.5 min arc; vertical separation: 30.3 min arc; numeral luminance: 13.1 cd/m^2 against a black background
- Helmet-mounted display (HMD) attached to the right side of a flight helmet
- Stabilization achieved by deflecting image (raster) in antiphase to display rotational displacement in pitch and yaw axes (Ref. 4)

Experimental Procedure

- Independent variables: vibration frequency, presence of image stabilization, type of image stabilization
- Dependent variables: reading time, reading error
- Observer's task: read each array as quickly and as accurately as possible
- 12 male observers: research workers with at least 20/20 vision; all had some practice using an HMD

Experimental Results

Reading time is converted to percentage increase in time/unit acceleration, $(\Delta t/t)\,(100/a)$, where: t = mean of pre- and post-vibration reading time; Δt = change in reading time under vibration; a = acceleration amplitude [m/sec^2 root mean square (rms)].

- Reading error is converted to percentage increase in error per unit acceleration, $(\Delta e/50)\,(100/a)$, where: e = change in number of reading errors under vibration; a = acceleration amplitude (m/sec^2 rms).
- Whole-body vibration at frequencies <10 Hz produces a decrement in helmet-mounted display (HMD) reading performance.
- Vertical (pitch) image stabilization alone improves reading performance (data not shown).
- Vertical (pitch) and horizontal (yaw) image stabilization greatly reduces vibration-induced reading performance decrement with the HMD.

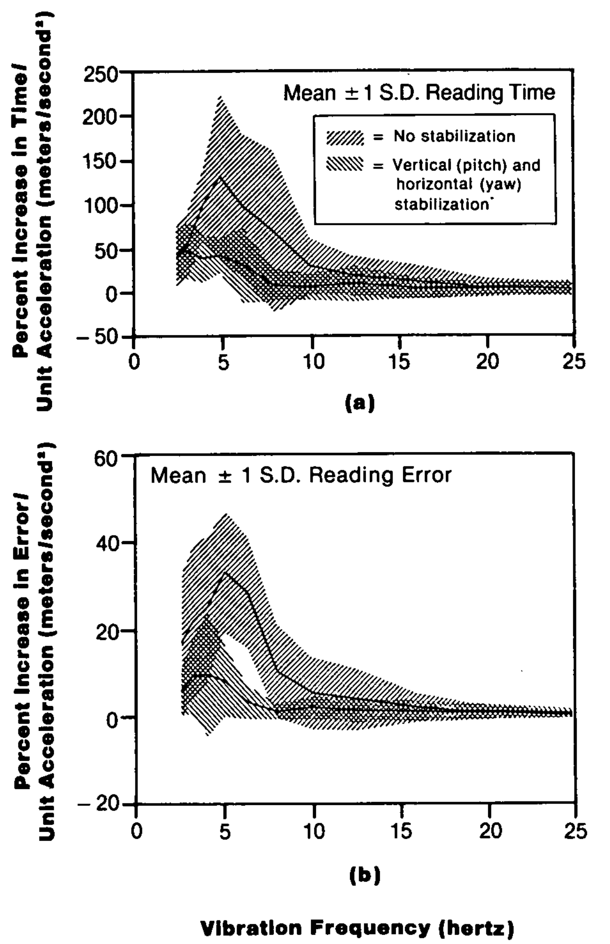


Figure 1. (a) Reading time and (b) reading error as a function of vibration frequency. (From Ref. 4)

Variability

Analysis of variance shows significant effects for observers, frequency, stabilization condition, and significant frequency × stabilization interaction for both reading time and error. Figures show ± 1 standard deviation about means.

Repeatability/Comparison with Other Studies

Similar effects of vibration and image stabilization are demonstrated with another type of HMD using 6 of the same observers (Ref. 4).

Comparison of these data with those from the frequency range 0.4-10 Hz shows similar trends in the effects of whole-body vibration on reading performance (Ref. 2).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Multiple axis vibration may affect amplitude of helmet motion and influence vibration-induced performance decrement.
- High levels of retinal illumination (e.g., during high ambient illumination) may reduce the performance decrement (Refs. 1, 3).
- Reading performance decrement is shown to be almost linearly related to z-axis whole-body vibration in amplitude range 0.28-2.8 m/sec^2 root mean square (Ref. 1).

Key References

1. Furness, T. A. (1981). *The effects of whole-body vibration on the perception of the helmet-mounted display.* Unpublished doctoral dissertation, University of Southampton, England.

2. Simpson, T. (1983, September). *Helmet-mounted display reading performance during low-frequency whole-body vibration.* Paper presented at the U.K Informal Group Meeting on Human Response to Vibration. Silso, Bedfordshire, England.

3. Wells, M. J. (1983). *Vibration-induced eye motion and reading performance with the helmet-mounted display.* Unpublished doctoral dissertation, University of Southampton, England.

*4. Wells, M. J., & Griffin, M. J. (1984). Benefits of helmet-mounted display image stabilization under whole-body vibration. *Aviation, Space and Environmental Medicine, 55,* 13-18.

Cross References

10.407 Transmission of vertical seat vibration to the head;

10.409 Factors affecting human performance during vibration;

10.418 Transmission of vibration to the eyes;

10.419 Transmission of vibration to helmets;

10.433 Vibration exposure duration: effect on visual performance

10.421 Model for Predicting the Effects of Vibration on Manual Control Performance

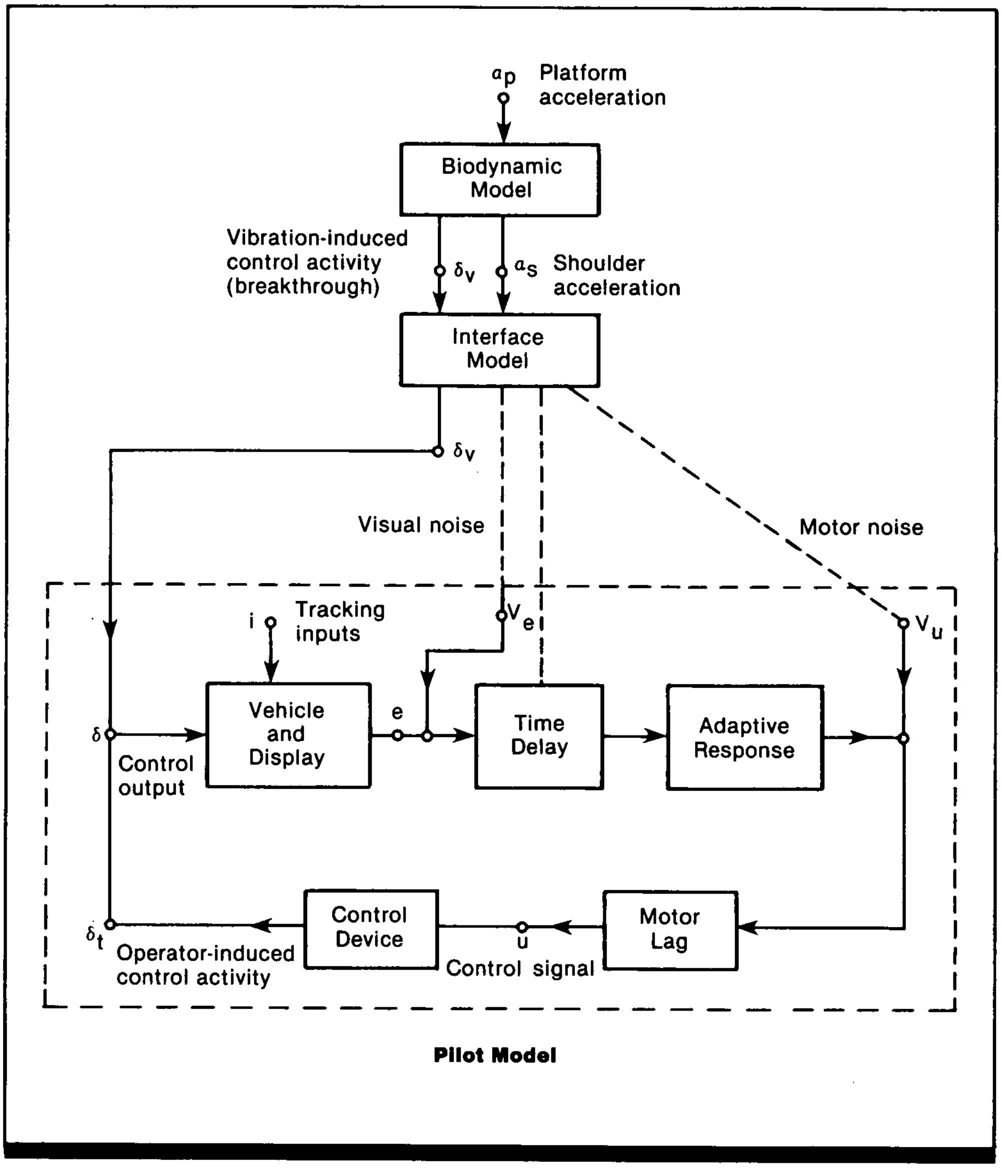


Figure 1. Diagram of the model structure; single-input, single-output control system with single-axis vibration input. (From Ref. 1)

Key Terms

Breakthrough; manual control; optimal control; tracking; vehicle dynamics; whole-body vibration

General Description

The model has been used to predict biodynamic response and tracking performance with various simple control systems in a variety of vibration environments. The model relates tracking performance during vibration exposure in any one of six axes to a variety of system and task parameters, including *vehicle dynamics*, tracking input variance, display gain, and characteristics of the control stick. The figure shows the three components of the model: a "biodynamic" model representing the mechanical response of the body to vibration, an "optimal control" (CRef. Handbook) model of the pilot/vehicle system, and an "interface" model relating the biodynamic response to changes in the parameters of the optimal control model. The biodynamic model is based upon empirical transmissibility data and relates the platform acceleration (α_p) to vibration-induced

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

activity at the control (δ_v, sometimes known as "break-through" or "feedthrough") and at the shoulder (α_s). The optimal control model relates system performance and pilot response to parameters of the control system, including the type of control used, the system dynamics and the tracking task performed. The operator is assumed to observe the displayed error (e) between the tracking input (i) and the system response with added visual noise (V_e), and to optimally adapt the response to compensate for inherent limitations and time delays. The form of adaptive response will depend upon both the system and the task. The operator's output (u) consists of the intentional response with added motor noise (V_u). In the absence of vibration, the system responds to the control output (δ_t). Effects of whole-body vibration on system performance are accounted for by a combination of increases in the visual and motor noise processes (V_e and V_u) and changes in the *effective pilot time delay* of the optimal control model. In addition, vibration breakthrough is added such that the system responds to the composite signal, δ. The interface model relates δ_v and α_s to these changes in the parameters of the optimal control model.

Applications

Can be used to investigate (a) the effects of different vibration environments on tracking performance for a given system, and (b) effects of changes in system parameters (control gain, task difficulty, etc.) on tracking performance in a given vibration environment. The model also has limited use as a research tool for investigating how operators' control behavior changes during vibration exposure.

Empirical Validation

The model was tested by comparing predicted control variance and root mean square (rms) tracking error with data obtained in three studies, demonstrating that:

1. The assumption that biodynamic response increases linearly with vibration magnitude is justified;
2. Biodynamic response is similar with three different vibration spectra;
3. With a control configuration of pitch-axis tracking, z- axis (vertical) platform vibration, and a stiff stick, the model predicts tracking performance to within ± 1 standard deviation for a range of electrical stick gains, rms tracking inputs, and display gains, and for all six vibration axes; and
4. The assumption that the relationship between pilot parameters and biodynamic response is independent of vibration axis appears valid.

Constraints

- Validation experiments used very simple systems and tasks; extensions to complex multi-input, multi-output systems were not demonstrated.
- Results were not validated for vibration at frequencies <2 Hz.
- The model predicts only overall root mean square performance; no indication of transient effects (e.g., response to impulses).
- The model assumes effects are independent of duration, and does not distinguish sources of disruption. e.g., visual blurring, operator workload, neuro-muscular effects, discomfort, etc.
- Most constraints for optimal control model apply.
- The model offers poor predictive ability for free-moving sticks and assumes no visually related interference.

Key References

1. Levison, W. H. (1978). Model for human controller performance in vibration environments. *Aviation, Space and Environmental Medicine, 49*, 321-237.

Cross References

9.508 Components of the manual control loop considering the human operator as an element in the control system;

9.514 Optimal gain levels in target acquisition;

9.515 Optimal gain levels in continuous control tasks;

10.419 Transmission of vibration to helmets;

10.423 Continuous manual control performance: interactive effects of control gain, control type, and vibration;

Handbook of perception and human performance, Ch. 39, Sect. 1.6

10.422 Manual Control Performance: Effects of System Dynamics and Vibration Frequency

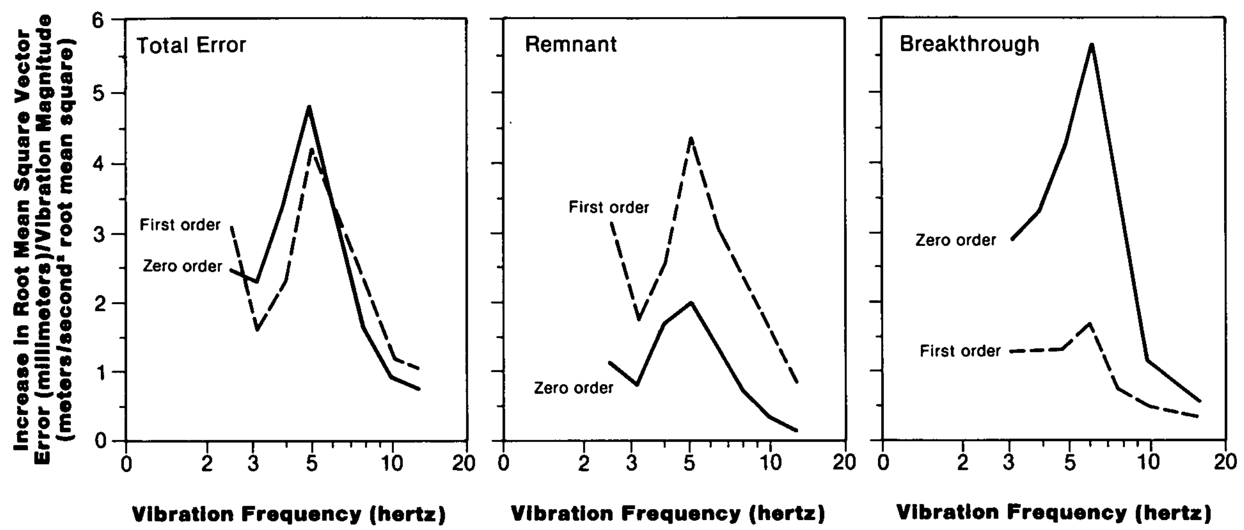


Figure 1. Increase in root mean square tracking error/vibration acceleration level observed during z-axis whole-body vibration. Total static error = 7 mm rms for zero order dynamics and 15 mm rms for first-order dynamics.

Key Terms

Body transmissibility; breakthrough; manual control; optimal control; tracking; whole-body vibration

General Description

Manual tracking is most sensitive to disruption by whole-body vibration in the region of 3-8 Hz. Sensitivity of a task to disruption depends upon both **system dynamics** and vibration frequency content. Dynamics with a simple gain (zero-order dynamics) transmit all frequencies equally. Direct transmission of vibration through the body and into the control system (breakthrough) therefore contributes a large proportion of error in zero-order systems. Dynamics with pure integration (first-order dynamics) attenuate in inverse proportion to frequency. First-order tasks are therefore less sensitive to direct breakthrough. However, first-order tasks are more sensitive to other forms of vibration-induced disruption.

Applications

High-magnitude, low-frequency vibration environments in which continuous manual tasks are to be performed.

Methods

Test Conditions

- Observers viewed a stationary 100 × 100 mm oscilloscope; viewing distance = 1.0 m; observers sat on a hard, wooden seat with semi-rigid seat back and moving footrest; observers held a two-axis isotonic (free-moving) side-arm joystick control attached to the moving seat frame
- Forcing function: filtered pseudo-random-binary sequences with flat amplitude spectrum up to 0.1 Hz, attenuated by 20 dB at 1.0 Hz, and by 20 dB per octave thereafter; independent forcing functions in each axis
- Control gain optimized with no vibration prior to experiment
- Sinusoidal, vertical (z-axis) seat vibration at 2.5, 3.15, 4.0, 5.0, 6.3, 8.0, 10.0, and 12.5 Hz at acceleration magnitudes of 1.9, 1.7, 1.5, 1.5, 1.5, 1.5, 1.9, and 2.4 m/sec^2 root mean square respectively; zero-order (pure gain and first-order (gain and integration) system dynamics
- Subject first performed task with no vibration then with eight vibration conditions in balanced order, and final run with no vibration
- 2-min tracking runs

Experimental Procedure

- Independent variables: vibration frequency, acceleration magnitude, system dynamics
- Dependent variables: root mean square tracking error, proportion of tracking error correlated with vibration (breakthrough), proportion of tracking error uncorrelated with either task or vibration (remnant)
- Subject's task: two-axis continuous pursuit tracking
- 8 trained subjects in each of two groups

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Zero-order and first-order control groups show similar increases in total root mean square (rms) vector tracking error during vibration exposure.
- Zero-order group shows significantly more breakthrough; first-order group shows more remnant.
- With zero-order control, the total increase in rms vector error is approximately proportional to the breakthrough amplitude.
- With first-order control, the increase in rms error is considerably greater than could be accounted for by breakthrough alone.
- Performance is most affected by vibration in the region of major body resonances, ~5 Hz.

Variability

No information on variability was given.

Constraints

- Control gain optimized in no-vibration condition (CRef. 10.423).
- Results relate only to pursuit displays (some evidence that compensatory first-order displays produce less remnant).
- Remnant includes possible disruption due to visual blurring, neuromuscular effects, operator workload and discomfort, and nonlinear strategies.
- Results relate to overall mean performance and do not allow precise prediction of effects on particular observers for particular conditions.
- Hand supports or arm-rests may reduce disruption.

Key References

1. Allen, W. A., Jex, M. R., & Magdaleno, R. E. (1973). *Manual control performance and dynamic response during sinusoidal vibration* (AMRL-TR-73-78). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory. (DTIC No. AD773844)

*2. Lewis, C. H. (1980). *The interaction of control dynamics and display type with the effect of vibration frequency on manual tracking performance*. Paper presented at the UK Group Meeting on Human Response to Vibration, Swansea, Wales.

3. Lewis, C. H., & Griffin, M. J. (1978). A review of the effects of vibration on visual acuity and continuous manual control. *Journal of Sound and Vibration, 56*, 415-457.

4. McLeod, R. W. & Griffin, M. J. (1986). *A design guide for visual displays and manual tasks in vibration environments. Part II. Manual tasks* (ISOR-TR-134). Southampton, England: Southampton University.

Cross References

9.527 Inherently unstable dynamics: the critical tracking task;

10.406 Factors affecting vibration transmission through the body;

10.409 Factors affecting human performance during vibration;

10.421. Model for predicting the effects of vibration on manual control performance;

10.423 Continuous manual control performance: interactive effects of control gain, control type, and vibration

10.423 Continuous Manual Control Performance: Interactive Effects of Control Gain, Control Type, and Vibration

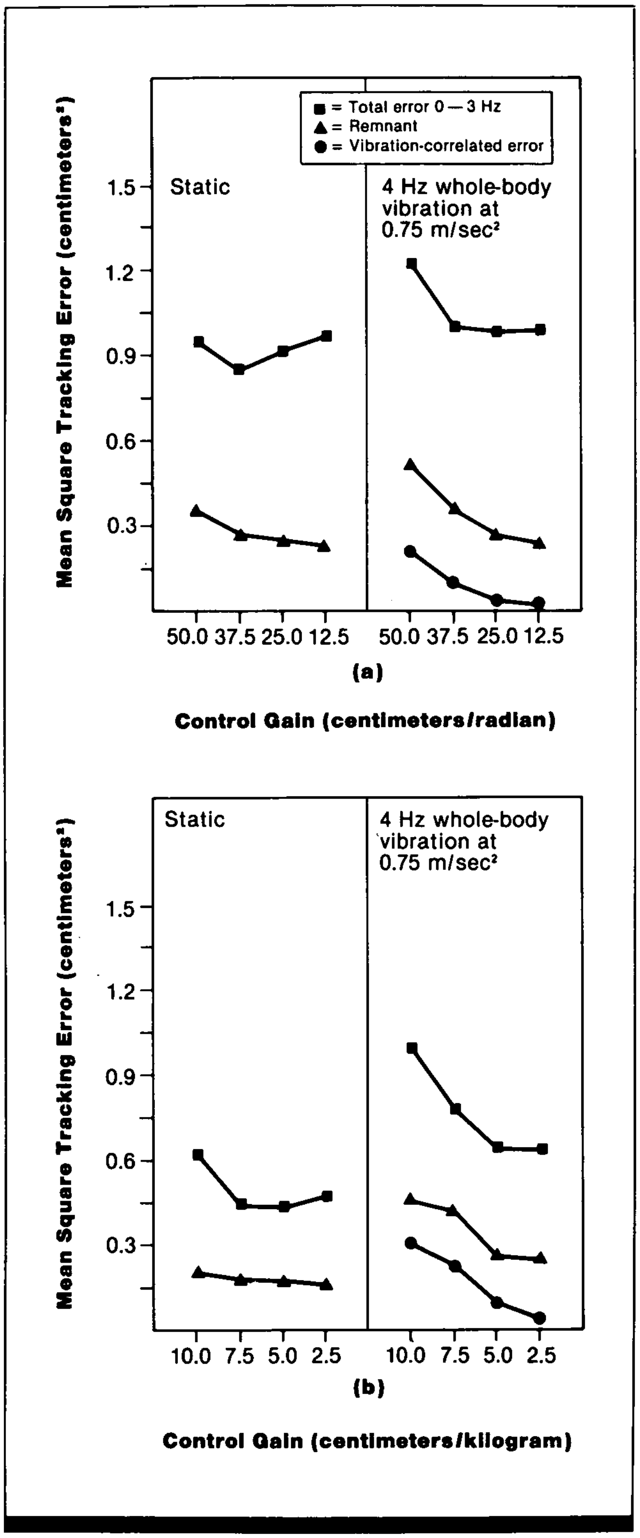


Figure 1. Mean tracking performance for (a) isotonic stick and (b) isometric stick. (From Ref. 2)

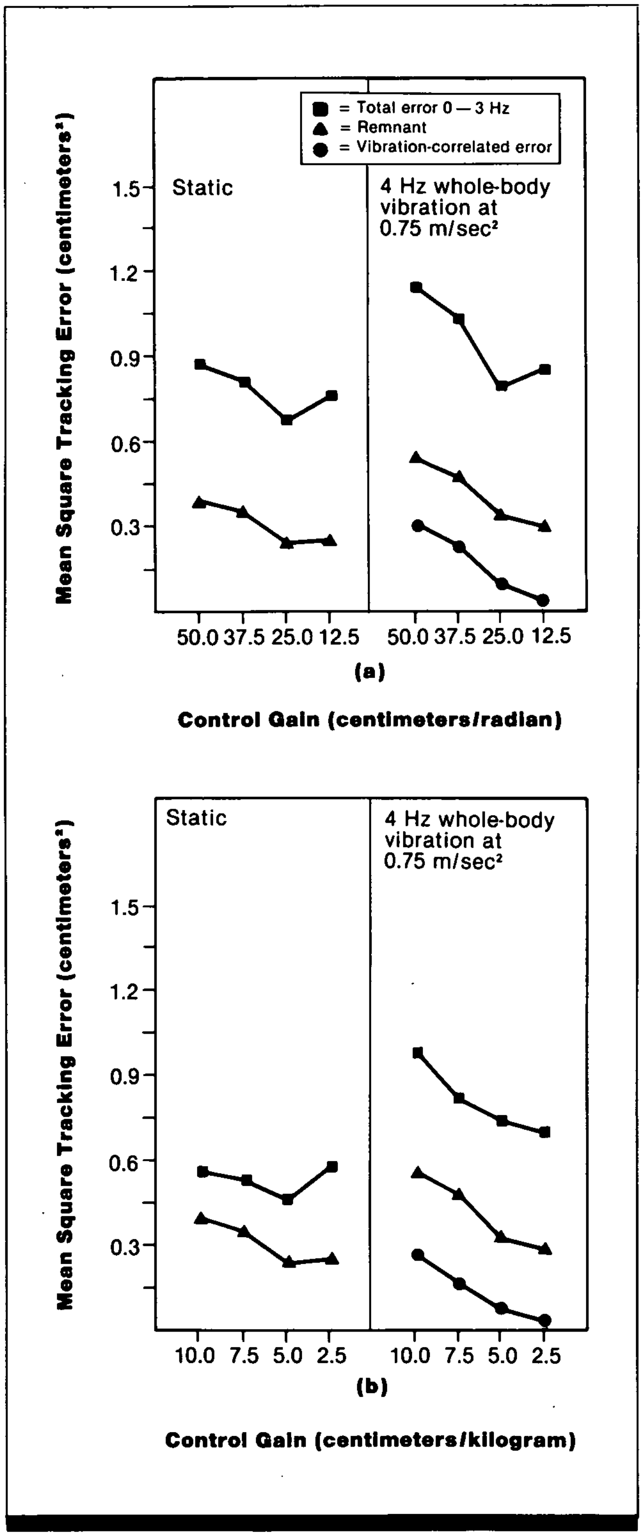


Figure 2. Mean tracking performance for (a) isotonic knob and (b) isometric knob. (From Ref. 2)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Breakthrough; joysticks; manual control; optimal control model; rotary controls; system dynamics; tracking error; whole-body vibration

General Description

Tracking error in pursuit tracking caused by direct transmission of vibration through the body and into the control system (breakthrough) is approximately proportional to control gain. Minimum total error occurs at lower gain with vibration rather than in static conditions, even when breakthrough-induced error is removed. Translational body motion can induce considerable rotary motion at the controlling limb; rotary knobs can therefore show as much breakthrough as joysticks.

Methods

Test Conditions

- Vibration frequencies of 0 or 4 Hz; isometric (rigid), isotronic (free-moving) joystick and rotary knobs; four levels of control gain per control
- Sinusoidal, vertical (*z*-axis) seat vibration at a magnitude of 0.75 m/sec^2 root mean square
- Subject viewed a stationary 100 x 100 mm oscilloscope display; viewing distance = 1.0 m
- Subjects sat on a hard wooden seat with semi-rigid seat back and stationary footrest
- 330-sec tracking run

Experimental Procedure

- 2 x 4 factorial with subjects as randomized blocks, for each control
- Independent variables: vibration frequency, type of control, level of control gain
- Dependent variables: total mean square tracking error, proportion of tracking error correlated with vibration (breakthrough), proportion of tracking error uncorrelated with either task or vibration (remnant)
- Subject's task: perform pursuit tracking in horizontal axis, system dynamics a pure gain
- Subjects given 4.5-hr training in static conditions
- 4 subjects, right-handed males

Experimental Results

- Optimum control gain for minimum total error is lower with vibration than static conditions.
- Breakthrough is reduced with decreasing control gain, but is as large for rotary controls as for joysticks.
- Remnant is significantly increased by vibration at the highest gain for the isotonic stick and at the higher two gains with the isometric stick, but not at lower gains; there are similar effects for rotary knobs
- Greater high-frequency phase lags occur with the isotonic stick than with either isometric knob.

Variability

No information on variability was given.

Constraints

- Small number of subjects were used and received only static condition training.
- There was incomplete randomization of order of presentation of controls.
- Zero-order (pure gain) system dynamics were used. In more complex systems, direct vibration breakthrough at high frequencies will be less important due to attenuation by the system dynamics (CRef. 10.422).

Key References

1. Levison, W. H., & Houck, P.D. (1975). *Guide for the design of control sticks in vibration environments* (AMRL-TR-74-127). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Lab. (DTIC No. ADA008533)

*2. Lewis, C. H., & Griffin, M. J. (1977). The interaction of control gain and vibration with continuous manual control performance. *Journal of Sound and Vibration, 55*, 553-562.

3. Lewis, C.H., & Griffin, M.J. (1978). A review of the effects of vibration on visual acuity and continuous manual control. *Journal of Sound and Vibration, 56*, 415-457.

Cross References

9.508 Components of the manual control loop considering the human operator as an element in the control system;

10.406 Factors affecting vibration transmission through the body;

10.421 Model for predicting the effects of vibration on manual control performance;

10.422 Manual control performance: effects of system dynamics and vibration frequency

10.424 Data Entry Performance During Vibration

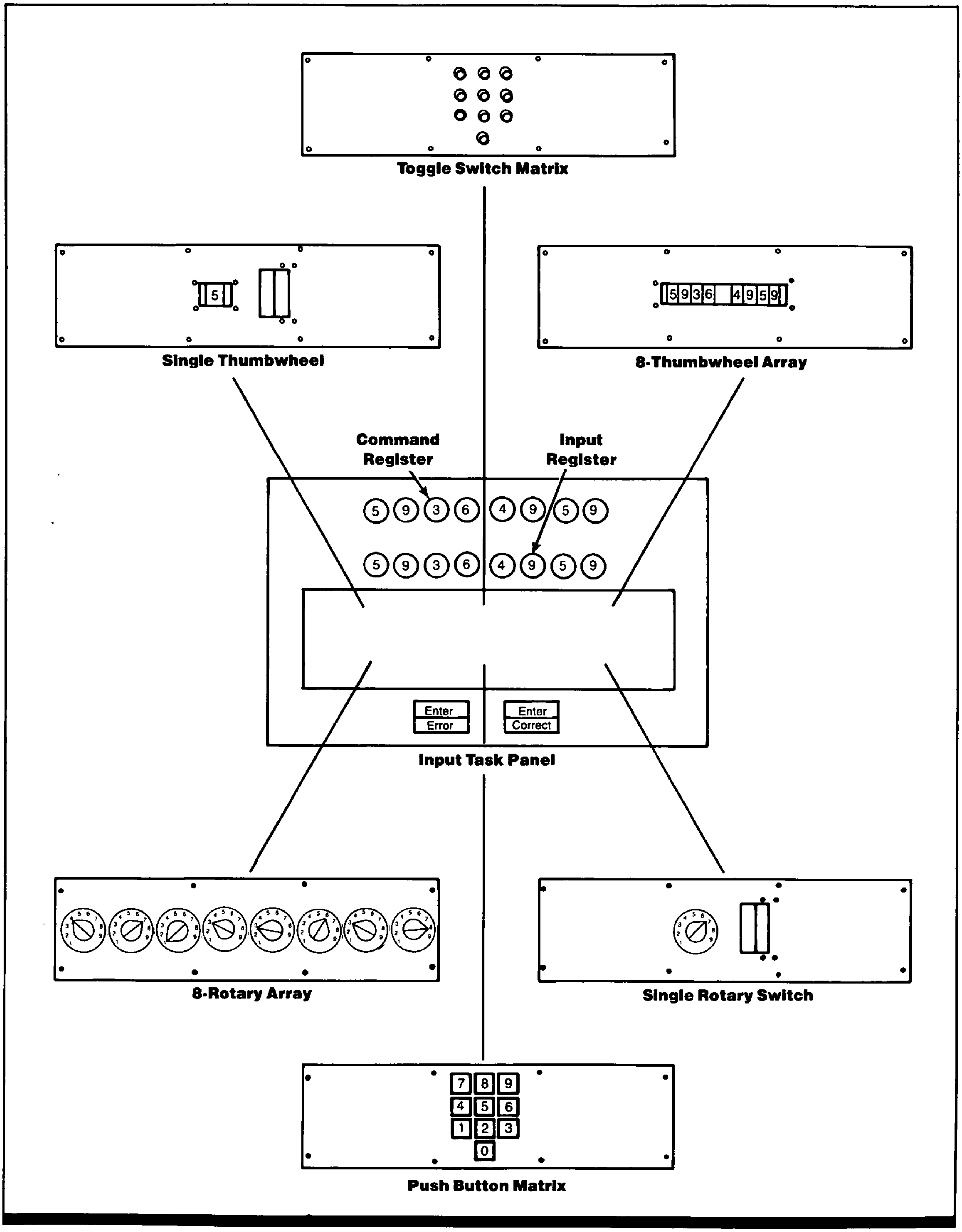


Figure 1. Six types of decimal input devices that were compared for speed, accuracy, and subject preference. Devices located on panel as shown. (From Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Data entry; decimal input devices; error rate; pushbuttons; rotary selector switches; thumbwheels; toggle switches; whole-body vibration

General Description

None of six decimal input devices examined is optimal in terms of speed, accuracy, and subject preference. The device operated with the greatest speed (pushbutton matrix) tends to be the least accurate, while the slowest device (thumbwheel array) tends to be the most accurate. Subjects prefer to operate the faster devices. When subjects are first exposed to vibration, it significantly decreases accuracy (Exp. 2); but they tend to compensate for this decrement by slowing their response times to maintain accuracy (Exp. 3). No device is consistently superior in both speed and accuracy under high-vibration conditions.

Applications

Discrete input devices for use in high-magnitude acceleration environments. For operational environments involving acceleration magnitudes and requiring only a rank ordering of devices with respect to speed of operation, design decisions may be based upon data from nonvibration environments. For use in high-acceleration environments, or if speed/accuracy trade-offs may be important, comparative evaluation under vibration is indicated.

Methods

Test Conditions

- Panel shown in Fig. 1; all six devices used in Exps. 1 and 2; only thumbwheel array, rotary array, and pushbutton matrix used in Exp. 3
- Thumbwheel and rotary-switch arrays are parallel-input devices; subject set value for each digit for entire eight-digit data word and could correct errors until entire word was input
- Pushbutton and toggle matrices are serial-input devices; subject actuated a control for each of eight digits; errors not correctable after control actuated
- Single rotary switch and thumbwheel are serial-input devices; subject set position for each of eight digits and pressed pushpad to input whole number after setting each digit; error correctable until pushpad was pressed
- COMMAND register displayed word subject was to enter; four serial-input devices used INPUT register to display entered digits; subject pressed ENTER ERROR pushpad if error noted or pressed ENTER CORRECT pushpad to signify a correct entry
- Testing conditions: (Exp. 1) sound-deadened room, subjects seated at desk and wore standard office clothes; (Exps. 2 and 3) in multiple-stress laboratory; subjects strapped to padded seat (with ~13 mm of firm felt) and wore overalls, headsets, lightweight flying gloves, and heart and respiratory monitoring instruments
- Random vertical vibration with bandwidth of 2-30 Hz; peak at 13 Hz; levels of 0.0 and 0.5 root-mean-square acceleration (RMS g) (Exp. 2); levels of 0.0, 0.2, 0.4, 0.6 and 0.8 RMS g (Exp. 3)

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: data entry device, vibration, level of vibration
- Dependent variables: insertion time (defined as time to enter eight-digit data word); percentage of recognized and unrecognized digit errors and word errors; subjective estimation of speed, accuracy, and preference for device; heart and respiration rates
- Subject's task: observer COMMAND register, input same data word on test device, and compare INPUT and COMMAND registers; correct any errors if possible, or press ENTER ERROR pushpad; if correct, press ENTER CORRECT pushpad
- 10 subjects in Exp. 1; 9 of these and 3 others (with equivalent training) for Exp. 2; 10 of these (in Exp. 2) for Exp. 3; all qualified pilots with engineering degrees; 28-47 yrs. of age; 50-5500 hrs flight experience

Experimental Results

- Average insertion time is reduced from 18.0-13.6 sec over the first half of Exp. 1 and changes very little throughout subsequent studies. Average error rates show a low but steady improvement over the three investigations.
- In Exp. 1 (using only last half of trials), there is a significant difference ($p <0.01$) among control devices in terms of insertion time, with fastest times for the pushbutton matrix, closely followed by the toggle matrix; all thumbwheel devices are equivalent and slowest, while rotary-switch devices are equivalent and intermediate. There are significant differences among devices ($0.01 < p < 0.05$) on all error indices except unrecognized digits, with the error rate generally lowest on the thumbwheel array. Subjects most often prefer the pushbutton array and estimate it to be fastest, while accuracy is thought to be the highest with the thumbwheel array.
- In Exp. 2, operation under 0.5 RMS g vibration is ~4% slower than under no vibration ($p <0.01$). The pushbutton and toggle matrices are equivalent and significantly faster in insertion time ($p >0.01$) than the other four devices, which are also equivalent. All four error indexes show poorer performance with vibration than without it ($p <0.01$). Accuracy is generally highest with the thumbwheel array, but accuracy is also high with the toggle matrix. The pushbutton matrix is most often preferred and estimated to be the fastest device, but none is believed to be most accurate.
- In Exp. 3, both the level of vibration and the type of device significantly affect insertion time ($p <0.01$). Insertion times for the 0.6 and 0.8 RMS g vibration levels are equivalent and significantly greater ($p <0.01$) than the other three levels, which are also equivalent. Insertion time differs significantly among the three devices ($p <0.01$), with the pushbutton matrix the fastest and the thumbwheel array the slowest. The interaction between devices and vibration is significant ($p <0.01$); the greatest increase in insertion time due to vibration is shown for the thumbwheel array and the least for the rotary array. Only unrecognized word errors show a significant difference ($p <0.05$) between devices, with the pushbutton matrix showing the lowest error rate and the thumbwheel array the highest. The effect of vibration is not significant for any device on any error index. The interaction between devices and vibration level is significant for errors ($p <0.01$), with high vibration degrading pushbutton matrix accuracy the most and affecting the thumbwheel array the least. The highest level of vibration, 0.8 RMS g, can cause intense discomfort.

Variability

There were significant ($p <0.01$) between-subject differences in each of the three experiments.

Repeatability/Comparison with Other Studies

The results of these three experiments agree fairly closely.

Constraints

• The real world vibration spectrum is not expected to be identical with the random vertical vibration tested here; therefore the generalizability of the results is difficult to determine.
• Relatively little vibration is seen in the region of major body resonances (3-8 Hz).
• For vibration environments having different spectral content, or vibration in other axes, interactions with devices may have an effect, so that 0.4 m/sec^2 root mean square should not be considered a general threshold.
• Orientation and position of input devices relative to subject is not reported.
• Results may be specific to particular input devices used in the study. In practice, comparative evaluation is recommended.
• Provision of arm rests or finger grips may reduce effects of limb motion.
• Other factors, such as operator workload and discomfort, may interact with vibration to disrupt performance (CRef. 10.428).

Key References

*1. Dean, R. D., Farrell, R. J., & Hitt, J. D. (1969). Effect of vibration on the operation of decimal input devices. *Human Factors, 11*, 257-272.

Cross References

10.428 Effect of vibration magnitude on discomfort;

12.403 Legend switches;

12.405 Toggle switches: factors affecting activation time;

12.412 Control type, location, and turbulence: effect on data entry performance;

12.413 Rotary selector switches;

12.416 Rotary controls: spacing, diameter, and orientation;

12.423 CRT touch screen devices

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

10.425 Manual Control Performance: Effects of Vertical Z-Axis Oscillatory Motion at Frequencies Below 1 Hz

Table 1. Effects of motion on task performance.

Task	Vertical acceleration rms (frequency)	Effect on performance	Motion sickness	Source
1. Tracking (unsupported arms)	0.24 m/sec^2 (0.17 Hz)	Severely degraded	no	Study 1 (Ref. 1)
2. Keyboard digit punching	0.24 m/sec^2 (0.17 Hz)	Unaffected	no	Study 1 (Ref. 1)
3. Tracking target with joystick (supported arms)	0.31 m/sec^2 (0.17 Hz)	20% increase in errors and acquisition time	no	Study 1 (Ref. 1)
4. Critical tracking—following meter needle with rotary control	0.15 m/sec^2 (0.19 Hz)	Unaffected	no	Study 2 (Ref. 2)
	0.5 m/sec^2 (0.25 Hz)	Scores reduced by 15%	yes	Study 2 (Ref. 2)
5. Navigational plotting	0.15 m/sec^2 (0.19 Hz)	Unaffected	no	Study 2 (Ref. 2)
	0.5 m/sec^2 (0.25 Hz)	20% fewer tasks completed	yes	Study 2 (Ref. 2)

Key Terms

Low frequency motion; manual control; motion sickness; oscillatory motion; ship motion; tracking; whole-body vibration

General Description

Manual control task performance is affected by vertical z-axis motion at frequencies of 0.1-0.3 Hz, particularly on tasks involving unsupported arm movements. Under ship-motion conditions, tracking, tracing, and navigational plotting are affected by magnitudes >0.2 m/sec^2 root mean square (rms). At greater magnitudes, motion sickness (which may include vomiting) will occur. Motion sickness may directly or indirectly affect performance, motivation, and safety.

Applications

Any vehicle in which low-frequency motion is present, particularly marine craft such as ships, hovercraft, hydrofoils, small boats, and rafts. Problems may also occur in aircraft and automobiles.

Methods

Test Conditions

Study 1 (Ref. 1)

- Three manual control tasks performed in ship-motion simulator
- Tasks repeated throughout 50-min session
- Vibration frequency = 0.17 Hz; vertical acceleration = 0.24 m/sec^2 rms (Tasks 1 and 2) or 0.31 m/sec^2 rms (Task 3)
- Pre-trial training established non-vibration performance baseline

Study 2 (Ref. 2)

- Two manual control tasks performed at sea
- Tasks performed repeatedly, with rests, throughout 4-hr voyage
- Vibration frequency was 0.19 or 0.25 Hz; vertical acceleration was 0.5 or 0.15 m/sec^2 rms
- Pre-trial training established non-vibration performance baseline

Experimental Procedure

Study 1

- Independent variable: vibration or no vibration (baseline)
- Dependent variables: task performance, symptoms of motion sickness
- Task 1: tracing geometrical patterns with pencil (arms unsupported); Task 2: keyboard digit punching (four-digit numbers); Task 3: tracking randomly moving target on screen with joystick (arms supported)
- 10 subjects: 8 males, 2 females

Study 2

- Independent variables: vibration or no vibration (baseline), acceleration magnitude
- Dependent variables: task performance, symptoms of motion sickness
- Task 4: critical tracking of randomly fluctuating meter needle with rotary control knob (minimization of biodynamic interference encouraged); Task 5: cognitive and manipulative navigational plotting task
- 17 male subjects

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Experimental Results

- Effects of motion on task performance are summarized in Table 1.
- No motion sickness symptoms occur during Tasks 1, 2, 3 or at the lower motion condition for Tasks 4 and 5.
- The higher motion for Tasks 4 and 5 produced motion sickness symptoms in all subjects and vomiting in 16 of 17 subjects.

Constraints

- Motion in axes other than vertical may also have an effect.
- Losses in performance depend on specific tasks. Similar tasks may be affected differently because of small but important differences, such as limb or body support or restraint.
- Manual performance may be affected directly by motions, as in Tasks 1, 2, 3 at low accelerations, while high accelerations will produce motion sickness which may further degrade tasks by affecting motivation and concentration (CRef. 10.426).
- Effects of different frequencies >1 Hz are not predicted.

Key References

*1. McLeod, P., Poulton, C., duRoss, H., & Lewis, W. (1980). The influence of ship motion on manual control skills. *Ergonomics, 23,* 623-634.

*2. Wiker, S. F., Pepper, R. L. & McCauley, M. E. (1980). *A vessel class comparison of physiological, affective state and psychomotor performance changes in men at sea* (USCG-D- 07-8). Washington, D.C.: United States Coast Guard. (DTIC No. ADA098047)

Cross References

10.409 Factors affecting human performance during vibration;

10.426 Factors affecting incidence of motion sickness caused by low-frequency vibration

10.426 Factors Affecting Incidence of Motion Sickness Caused by Low-Frequency Vibration

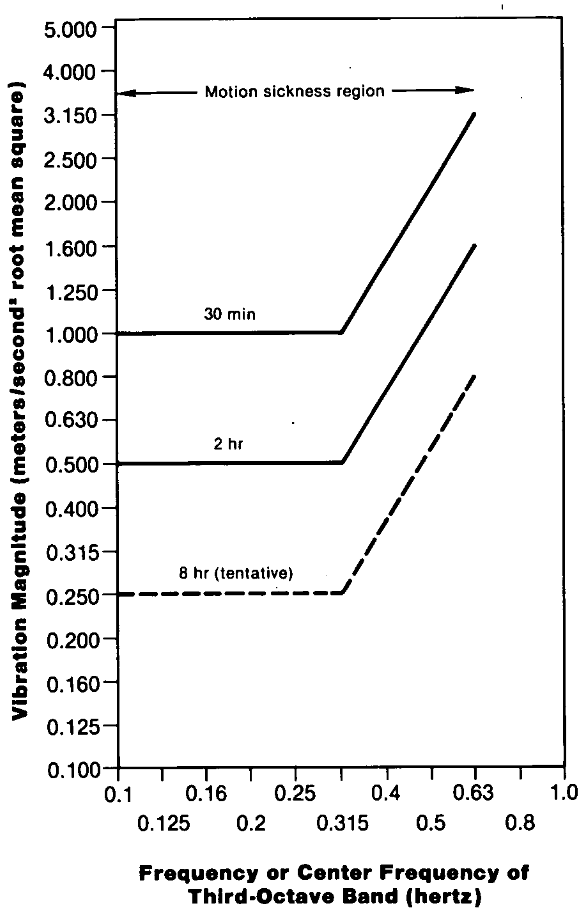

Figure 1. Severe discomfort boundaries (international standard) for whole-body *z*-axis vibration of 0.1-0.63 Hz; boundaries for 0.1-0.315 Hz represent 10% vomiting incidence in unadapted men. (From Ref. 4)

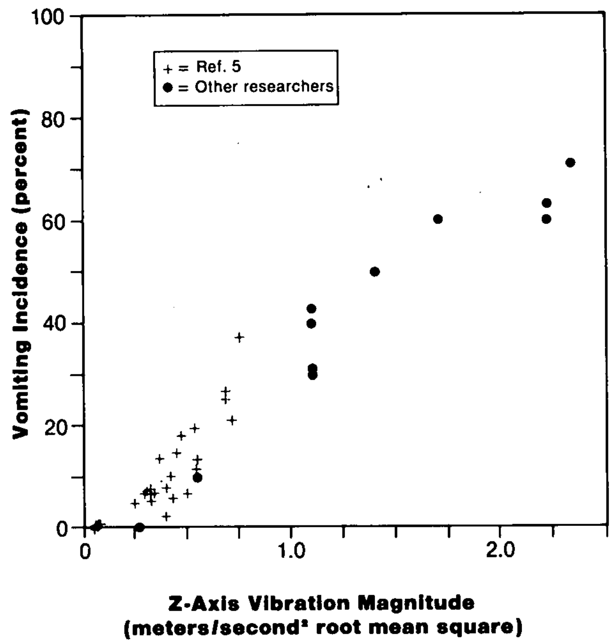

Figure 2. Vomiting incidence as a function of 2-hr *z*-axis vertical rms acceleration. Data points from Refs. 3, 9, and 10 (as well as Ref. 5) are included.

Key Terms

Low frequency vibration; motion sickness; seasickness; simulator sickness; vibration discomfort; whole-body vibration

General Description

Motion sickness may be produced by low-frequency, vertical, *z*-axis vibration with frequency content <0.63 Hz. Laboratory experiments using simulators indicate that people are most sensitive at frequencies <0.3 Hz. Studies of passengers aboard ships confirm laboratory findings of a good correlation between *z*-axis root mean square (rms) acceleration magnitudes and vomiting incidence. Information on other variables, both of the motion and of the population exposed to it, can increase the accuracy of seasickness predictions.

Applications

Any environment in which low-frequency motion is present, particularly marine craft such as ships, hovercraft, hydrofoils, small boats, and rafts. Problems may also occur in aircraft, automobiles, and simulators.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods (across studies)

Test Conditions

- Most laboratory experiments used continuous, sinusoidal, single-frequency stimuli; subjects seated with no external visual reference; frequencies 0.083-0.7 Hz, magnitudes from 0.28-5.6 m/sec^2 rms (but not all magnitudes at all frequencies); exposure duration: 2 hr
- Field studies used 22 voyages on 4000-ton ferry; z-axis and pitch frequencies centered on 0.22 Hz; voyage rms magnitudes up to 0.8 m/sec^2; sea conditions from calm to very rough; voyage duration: 4 hr; motion recorded in all six axes continuously throughout voyages

Experimental Procedure

- Laboratory experiments used partial factorial design
- Field studies used large-scale questionnaire surveys of passengers
- Independent variables: vibration frequency, rms acceleration magnitude
- Dependent variables: vomiting incidence, illness rating
- Subjects for laboratory experiments: fit, young, unadapted, male volunteers, in groups of 20
- Subjects for field trials: general public, excluding frequent sea travellers (>6 times per year); 50-250 per voyage

Experimental Results

- Results of laboratory studies (Refs. 1, 3, 9, 10) and some additional data (Ref. 2) form the basis for the international standard shown in Fig. 1 (ISO 2631, Add. 2).
- The frequency region most likely to produce nausea is 0.1-0.3 Hz. In this region, 1 m/sec^2 rms acceleration will cause ~10% vomiting incidence in 1/2 hr.
- Field studies show that z-axis ship motion is usually of a single frequency but varies in amplitude. y-axis acceleration is sometimes as great as z-axis acceleration. Vomiting incidence varies closely with illness rating scale, although many people feel ill but do not vomit.
- Good correlation is seen between z-axis vertical rms acceleration magnitude, vomiting incidence, and illness rating (Ref. 5). Figure 2 compares these data with previous laboratory data. Correlation is best with z-axis motion and is slightly higher when other axes are included in the analysis.
- Number of persons seasick increases as voyage duration increases up to 4 hr.
- More females become seasick than males, in a ratio of ~3:2.
- Older persons tend to be seasick slightly less than younger persons.
- Regular travelers are generally more resistant to seasickness.
- Anti-motion-sickness drugs are not 100% effective.

Constraints

- Laboratory experiments used artificial environment, sinusoidal stimulation, and young male subjects.
- Field study was observational and uncontrolled. Passengers had freedom of action.
- Survey followed one ship on one sea route, through many voyages.
- Effects on crew were not assessed.
- Acclimatization and self-selection are likely.
- Secondary factors, e.g., heat, smell, eating, and posture, were not quantified but are believed to be consistent between voyages.
- Analysis of ship motion other than rms averaging may give equal or better predictions.

Key References

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Cross References

10.428 Effect of vibration magnitude on discomfort;

10.429 Model for predicting the discomfort of seated occupants of vehicles;

10.430 Effects of severe vibration

10.427 Vibration Perception Thresholds

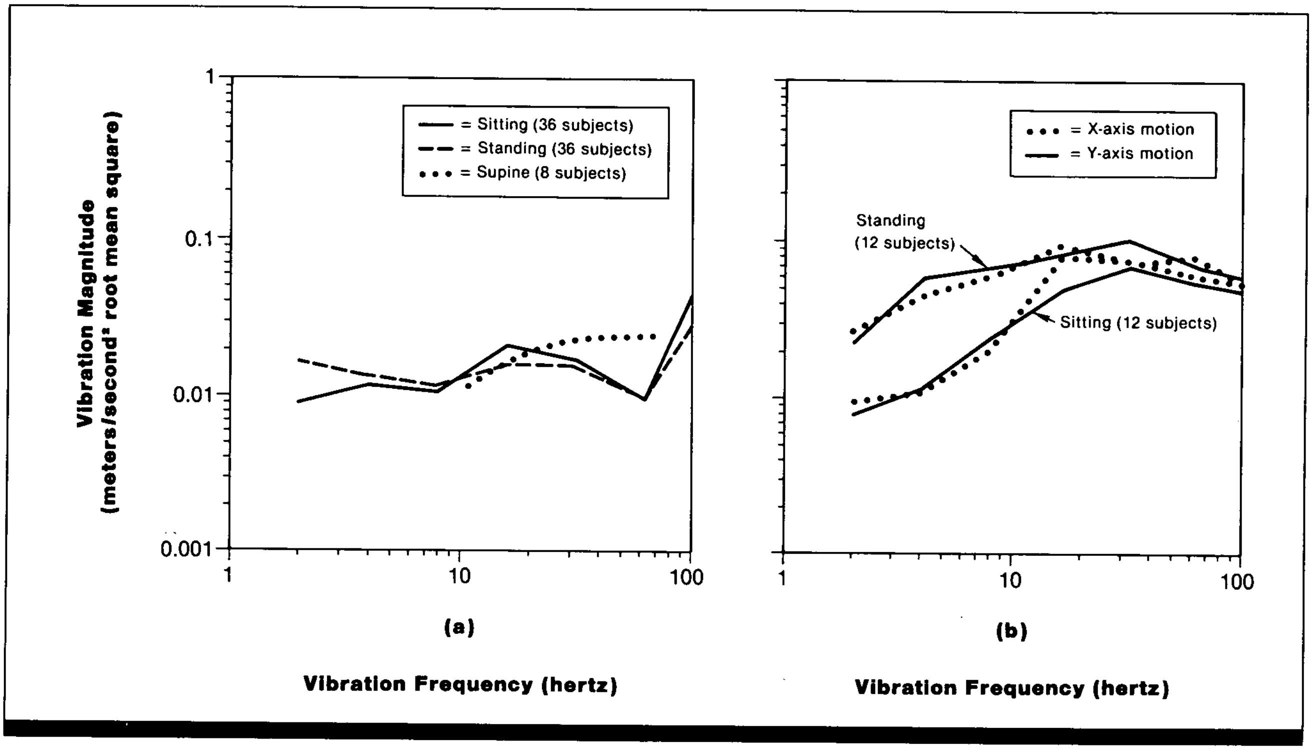

Figure 1. Median vibration perception thresholds for (a) subjects in three postures with vertical motion of the supporting surface and (b) subjects in two postures with fore-and-aft (*x*-axis) and lateral (*y*-axis) motion of the supporting surface. (From Ref. 5)

Key Terms

Vibration perception; whole-body vibration

General Description

Vertical whole-body vibration perception thresholds (the reciprocal of sensitivity) are similar between males and females tested under standing, seated, and supine conditions. Threshold is ~0.01 m/sec^2 root mean square (rms), between 2 and 100 Hz, for seated and standing conditions, and is similar for supine subjects (Fig. 1a). Horizontal (*x*- and *y*-axis) vibration thresholds are lower for seated subjects than for standing subjects (Fig. 1b).

Applications

Direction of vibration in buildings and other structures where very low magnitudes of vibration are likely to be encountered. Knowledge of motion perception thresholds also required for definition of motion simulator performance.

Methods

Test Conditions

- Sinusoidal vibration stimuli generated by electrodynamic vibrator, acceleration frequencies from 2-100 Hz, 11 stimulus magnitudes from 0.0002-0.16 m/sec^2, rms stimulus duration: 4 sec; background vibration on vibrator table <0.004 m/sec^2 rms with a frequency >50 Hz; vibration magnitude controlled to within 5% (sitting and standing subjects in Fig 1a), magnitudes adjusted by subjects (Fig. 1b) and supine subjects (Fig. 1a).
- Subjects were seated or stood on a rigid flat surface, eyes open, looking forward; seated subjects, feet supported on stationary footrest, upper legs horizontal, lower legs vertical, subjects unrestrained but required to maintain comfortable upright posture; standing subjects required to maintain comfortable upright posture; lying subjects supine with head, body, and feet in contact with vibrating surface; subjects dressed normally but with jackets and overcoats removed; standing subjects removed shoes.
- Ten trials per vibration magnitude and frequency; stimulus present on five of the ten stimulus-on periods
- Subjects cued by lights to indicate stimulus-on period and when to respond
- Stimulus conditions selected initially at random from seven vibration frequencies with 0.01 m/sec^2 rms magnitude; subsequent stimulus conditions selected to obtain appropriate range of responses
- Threshold for eight supine subjects (Fig. 1a) and 12 subjects exposed to horizontal vibration (Fig. 1b) determined by magnitude production; subjects adjusted stimulus magnitude until they could "just feel" vibration

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Experimental Procedure

- Signal detection
- Independent variables: presence or absence of vibration, vibration magnitude, vibration frequency
- Dependent variable: threshold, defined as the discriminability value for 75% hits and 25% false alarms: corresponds to $d' = 1.348$
- Subject's task: to report presence or absence of vibration during stimulus-on period (Fig. 1a)
- 36 subjects; 18 male and 18 female paid, unpracticed (research workers, technicians, students, and the general public)

Experimental Results

- Two d' values measured at each frequency are used in a sine interpolation to calculate a vibration magnitude corresponding to a d' value of 1.348. Corresponding vibration magnitudes indicate subject's perception thresholds.
- No significant ($p < 0.05$) differences between seated or standing males and females result at any frequency except 8 Hz. Seated females are less sensitive than males to 8-Hz vibration.
- At 8 Hz and below, subjects are significantly ($p < 0.05$) more sensitive to vibration when seated than when standing. At frequencies >16 Hz (except at 63 Hz) subjects are significantly more sensitive to vibration in the standing posture (Fig. 1a).
- Median thresholds are approximate to constant acceleration magnitude: 0.01 m/sec^2 rms.
- Thresholds for horizontal vibration are greater than those for vertical vibration at frequencies >10 Hz (Fig. 1b).
- At low frequencies, thresholds for standing subjects are higher than those for seated subjects (Fig. 1b)

Variability

No retest reliability measures were made. Review (Ref. 2) suggests reliability of threshold measurements has not been systematically investigated. Variability between subjects in threshold measurements in the seated posture is greatest at 31.5 Hz (0.0001-0.03 m/sec^2 rms). In the standing posture the range is greatest at 63 Hz (0.002-0.30 m/sec^2 rms) (Ref. 4). Variability between subjects is similar to that reported in Ref. 3.

Repeatability/Comparison with Other Studies

Findings are consistent with other studies (Refs. 2, 3).

Constraints

- Data are limited to frequency range of 2-100 Hz. At lower frequencies, <1 Hz, the range of values reported for threshold curves is much greater (Refs. 1, 2).
- Perception thresholds apply to the surface in contrast with the body. Padding or foam placed between the subject and vibrating surface will considerably alter vibration input to the subject (CRef. 10.431)
- Perception thresholds for standing subjects were obtained without shoes; the effect of footwear on the perception of vibration was not determined.

Key References

1. Benson, A. J., & Dilnot, S. (1981). *Perception of whole-body linear oscillation.* Paper presented to the United Kingdom Informal Group Meeting on Human Response to Vibration, Heriot-Watt University, Edinburgh, Scotland.

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*5. Parsons, K. C. (1981). *Whole body vibration perception thresholds of sitting, standing and lying subjects.* Paper presented to the United Kingdom Informal Group Meeting on Human Response to Vibration, National Institute of Agricultural Engineering/National College of Agricultural Engineering, Silsoe, Berkshire, England.

Cross References

3.106 Pressure and vibration sensitivity;

10.426 Factors affecting incidence of motion sickness caused by low-frequency vibration;

10.428 Effect of vibration magnitude on discomfort;

10.431 Transmission of vibration through seats

10.428 Effect of Vibration Magnitude on Discomfort

Key Terms

Subjective reaction; vibration discomfort; whole-body vibration

General Description

Increase in discomfort of seated subjects with increasing magnitudes of vertical (*z*-axis) vibration follows a Stevens Power Law of the form $\psi = k\theta^n$, where ψ is the subjective magnitude of the stimulus, θ is the physical magnitude of the stimulus, k is a constant determined by the units used, and n is the value of the exponent. Approximate unity is obtained for n. This implies that as root mean square (rms) magnitude of a stimulus doubles, subjective magnitude also doubles.

Applications

Evaluation of subjective reaction to vibration environments including quantification of the effects of changes in the magnitude of the vibration input on the sensation of vehicle occupants.

Methods

Test Conditions

- 8-Hz sinusoidal stimuli generated by an electrodynamic vibrator, five acceleration magnitudes from 0.5-2.5 m/sec^2 rms, five stimulus durations from 2-50 sec; 10 sec between stimulus presentations; acceleration waveform distortions <15%
- Subject seated on rigid flat seat with no backrest; feet supported on adjustable stationary footrest, upper legs horizontal, lower legs vertical; unrestrained but required to sit in comfortable upright position
- Two sessions per subject

Experimental Procedure

- Magnitude estimation
- Independent variables: magnitude and duration of 8-Hz vibration; random presentation order
- Dependent variable: subjective discomfort judged on a numerical scale where 0 represents no discomfort; upper limit of scale not defined; data from each subject normalized by equalizing geometric mean judgment of each subject
- Subject's task: verbally estimate discomfort of vibration
- All subjects given prior training in magnitude estimation
- 18 subjects, 15 males and 3 females, paid (research workers, technicians, students)

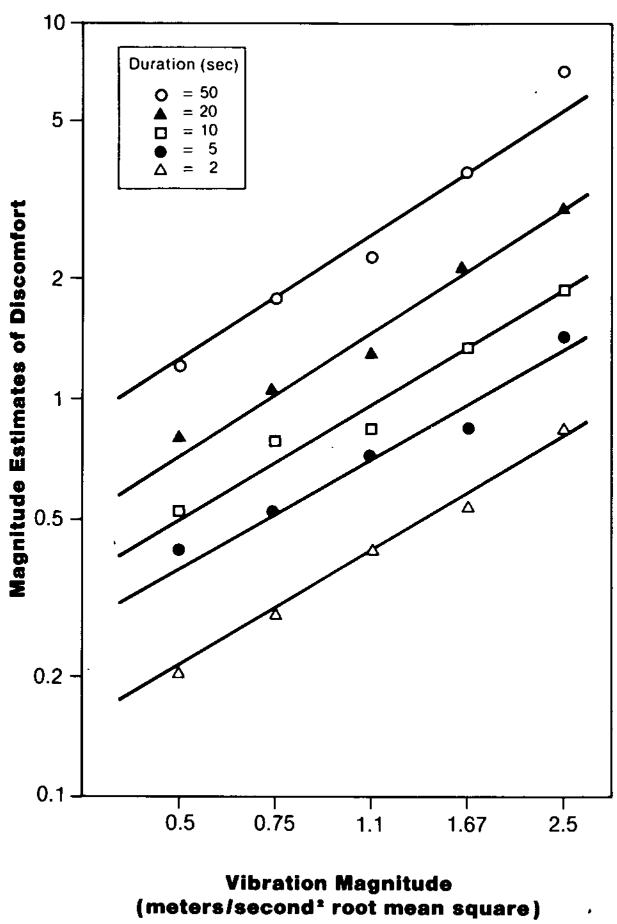

Figure 1. Discomfort estimates as a function of vibration magnitude. (From Ref. 2)

Experimental Results

- Figure 1 plots the geometric mean of equalized judgments of the 18 subjects.
- Curves were obtained by multiple regression analysis and are expressed by the following equation:

$$\log \psi = 0.964 \log a + 0.563 \log t - 0.60, \text{ i.e.,}$$
$$\psi = a^{0.964} (t^{0.563}/3.98)$$

where log ψ is the geometric mean of the magnitude estimates, a is the rms vibration (m/sec^2), and t is the duration of vibration (sec). Multiple correlation coefficient is 0.995.
- Discomfort increases with increasing vibration magnitude for stimulus durations between 2 and 50 sec. Rate of increase in discomfort becomes larger as vibration magnitude increases, but the relation is well approximated by a linear function. This is clearly justified by the high value of the multiple correlation coefficient.

Variability

Individual variability not reported, but 95% confidence limits for value of exponent n in magnitude growth function are 0.900 and 1.028. Data from Ref. 3 indicate high retest reliability. No significant differences ($p > 0.05$) found between groups of subjects retested after 1-2 months.

Repeatability/Comparison with Other Studies

Value of n obtained (0.964) is almost identical to 0.94 and 0.95 for male and female subjects, respectively, reported in Ref. 3. Data obtained from 13 subjects (Ref. 1) exposed to 10-Hz vibration yielded a value of n that varied from 0.82-1.39, with a mean value = 1.13, standard deviation = 0.18. Other studies (Refs. 3, 5) show that n varies with frequency of vibration. All values obtained are, however, close to unity.

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Constraints

- The linear relationship between discomfort and vibration magnitude is limited to moderate vibration magnitudes well above subjects' perception sensitivities and well below tolerance limits.
- Data are applicable only to vertical axis motion of seated subjects. Limited data suggest a similar relationship between vertical vibration magnitude and discomfort for standing subjects (Ref. 3).
- Subjects' discomfort is not quantified on an absolute scale. Table 1 is reproduced from a proposed revision of an existing standard concerning human response to vibration.
- Discomfort varies with the frequency of vibration (CRef. 10.429). A condition described as comfortable in one environment may be unacceptable in another environment.
- Discomfort resulting from exposure to vibration may also adversely affect task performance (CRef. 10.421).

Key References

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Cross References

10.421 Model for predicting the effects of vibration on manual control performance;

10.426 Factors affecting incidence of motion sickness caused by low-frequency vibration;

10.427 Vibration perception thresholds;

10.429 Model for predicting the discomfort of seated occupants of vehicles

Table 1. Scale of reactions to vibration.

Vibration Magnitude (m/sec²)	Subjective Reaction
<0.315	Not uncomfortable
0.315-0.63	A little uncomfortable
0.5-1.0	Fairly uncomfortable
0.8-1.6	Uncomfortable
1.25-2.5	Very uncomfortable
>2.0	Extremely uncomfortable

10.429 Model for Predicting the Discomfort of Seated Occupants of Vehicles

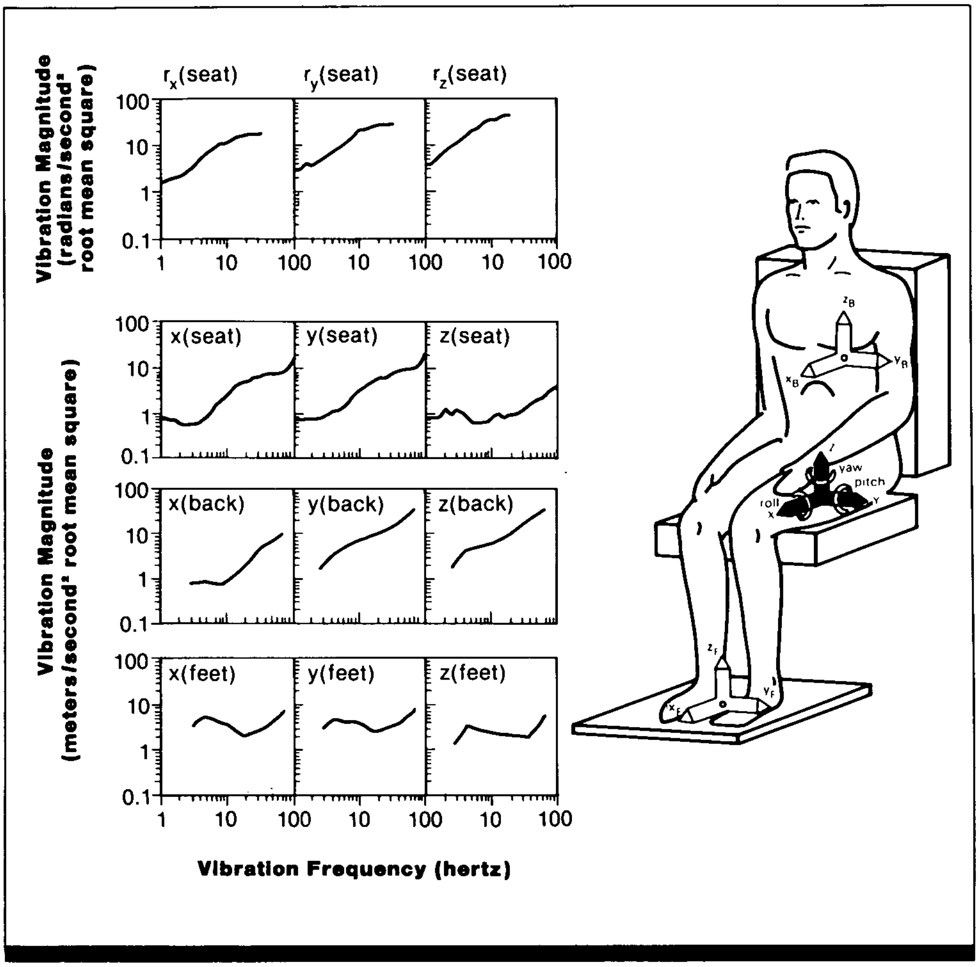

Figure 1. Median equivalent comfort contours. Corresponding input positions/axes are indicated on human figure.

Key Terms

Subjective reaction; vibration discomfort; whole-body vibration

General Description

A model of vibration discomfort assessed whole-body vibration in 12 input positions/axes; vertical, fore-and-aft, and lateral motion of the seat surface, backrest, and footrest; roll, pitch, and yaw motion of the squab (soft seat cushion). Equivalent comfort contours were determined in the laboratory for each axis (Refs. 3, 4, 5). Subjects compared motions in each axis with a reference [10 Hz, 0.8 m/sec^2 root mean square (rms)] sinusoidal vertical motion of the seat surface. Resulting median equivalent comfort contours indicate magnitudes of vibration across frequency which produce the same sensation of discomfort, irrespective of the frequency or axis or position. The figure shows relative discomfort produced by different motions. For example, at all frequencies, subjects are less sensitive to translational (x-axis or y-axis) motion of the footrest than vertical (z-axis) motion of the seat surface (Ref. 2). The model permits identification of the relative contribution to overall discomfort of motion in each of the 12 conditions. Overall discomfort of occupants can be expressed by a single number.

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Applications

Evaluation of subjective reaction to vibration environments in vehicles. The model enables comparison of discomfort in different complex multi-axis vibration environments. Identification of the input positions/axes and vibration frequencies causing most discomfort is possible.

Methods

• Acceleration measurements are made with transducers located between passengers and the vehicle seat and floor (Ref. 4); power spectral density functions $[G_i(f)]$ may be calculated for motions at each input. A frequency weighting $S_i(f)$ is calculated for each axis from the appropriate comfort contour $C_i(f)$:

$$S_i(f) = 0.8/C_i(f). \quad (1)$$

The weighted rms value (W_i = component ride value) of motion in each of the 12 axes is given by:

$$W_i = [\int_b^a G_i(f) \cdot S_i^2(f)df]^{1/2} \quad (2)$$

where a and b indicate the frequency range over which discomfort is to be considered, and i indicates which of the 12 axes is involved. The weighted rms values of motion in the 12 input axes are then combined by taking the square root of the sum of squares of the W_i:

$$\text{Overall ride value} = \left[\sum_{i=1}^{i=12} W_i^2\right]^{1/2} \quad (3)$$

The resulting value is the overall ride value for the occupant of that vehicle. Comparisons between vehicles may be made on the basis of their respective comfort values.

Empirical Validation

Model validation involved comparing results of objective analysis of vehicle rides with subjective assessments of vehicle occupants. A field test of six different vehicles in which 8 subjects were driven over 12 types of road resulted in the procedure described in the model most accurately predicting subject discomfort (Ref. 5). Eight other evaluated procedures were all less accurate.

Constraints

• The weighting functions covered a limited frequency range in some axes. This resulted from displacement limitations of equipment used to determine equivalent comfort contours.
• The effect of phase differences between vibrations in 12 input positions/axes has yet to be fully quantified.
• In cases where the vehicle ride contains impulsive components (i.e., ratio of peak to rms value of time history exceeds 6) the procedure will tend to underestimate vibration severity and discomfort. The root mean quad of the stimulus magnitude may then be more appropriate than the rms value (Ref. 5).
• Vibration inputs to vehicle occupants must be measured at the interface between occupant and vibrating surfaces of the seat and floor. Soft seats may considerably modify vibration input (CRef. 10.431).

Key References

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Cross References

10.426 Factors affecting incidence of motion sickness caused by low-frequency vibration;

10.428 Effect of vibration magnitude on discomfort;

10.431 Transmission of vibration through seats

10.430 Effects of Severe Vibration

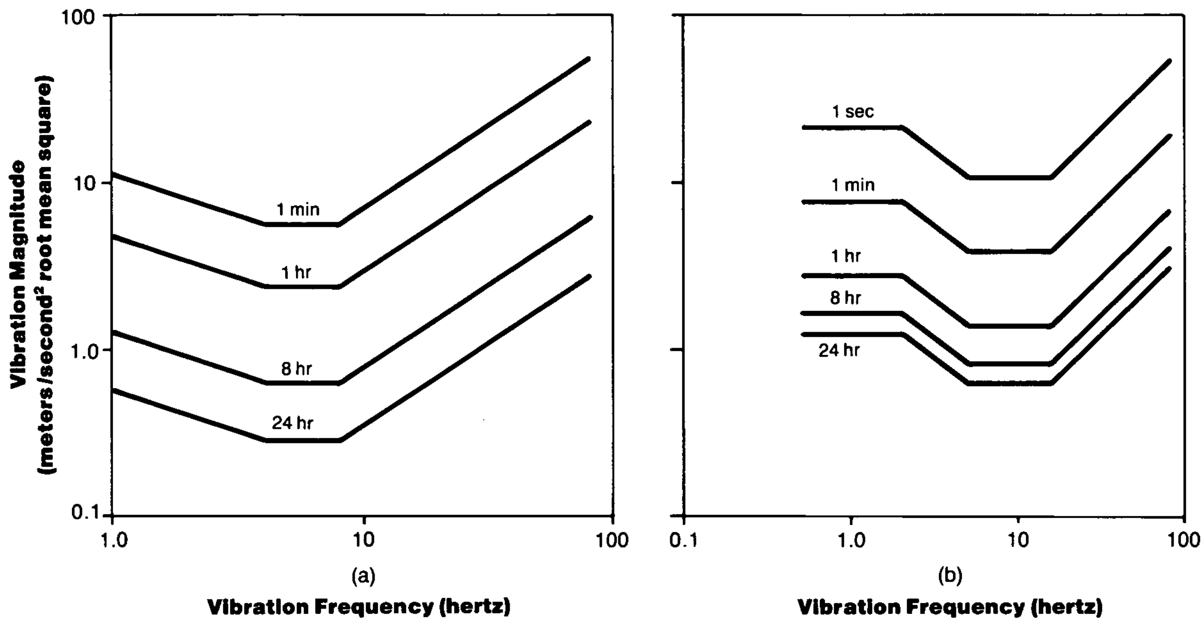

Figure 1. (a) Vibration exposure limits for safety and health defined in International Standard 2631 (1974); (b) Vibration conditions corresponding to a limiting Vibration Dose Value of 15 m/sec $^{1.75}$.

Key Terms

Vibration dose value; vibration exposure

General Description

Excessive vibration can be unpleasant or painful and may be a health hazard. In severe vibration environments, performance can be impaired directly or indirectly by pain or discomfort. Performance of tasks otherwise insensitive to vibration will, therefore, be affected by excessive vibration. Since vibration of aircraft and ground vehicles often increases with speed, maximum performance may be limited by crew sensation of severe motion.

International Standard 2631 (Ref. 2) specifies limits for maximum safe exposure to vibration frequency, duration, and direction (see Ref. 1). Later proposed procedures are more comprehensive, less ambiguous, and less constrained than those in the International Standard (Ref. 2). A Vibration Dose Value (VDV) is defined:

$$\text{Vibration Dose Value m/sec}^{1.75} = \left(\int_0^T a^4(t)dt\right)^{1/4} \quad (1)$$

where $a(t)$ is the frequency-weighted acceleration and T is total time in the day during which vibration may occur. The VDV is the magnitude of a 1-sec motion with an equivalent effect. For low crest factor motions, the dose value may be estimated as:

$$\text{Estimated Vibration Dose Value} = [(1.4 \times \text{rms value, m/sec})^2 \times (\text{duration, sec})]^{1/4} \times (\text{m/sec}^{1.75}). \quad (2)$$

High Vibration Dose Values indicate severe discomfort, pain, and injury, and point generally to the severity of the vibration exposures causing them. It is known that vibration magnitudes and durations, producing dose values in the region of 15 m/sec$^{1.75}$ will usually cause severe discomfort (Fig. 1b). It is reasonable to assume that increased exposure to vibration will increase risk of injury.

Applications

The methods indicate conditions at which the activities of subjects are likely to be disturbed due to severe discomfort and/or injury.

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Constraints

International Standard

- Limited to 1-80 Hz and low crest factor motion.
- Expression of vibration severity for complex motions requires reference to Amendment 1 of ISO 2631 (Ref. 5).
- Frequency weighting does not appear consistent with subject evaluations of vibration discomfort, especially at frequencies >8 Hz.
- Time-dependency does not appear consistent with expectations or experience at long (>4 hr) or short (<10 min) durations.
- Short durations (<1 min) and repeated shock motions cannot be assessed.
- Evaluation of intermittent motions is difficult.
- While many studies have referenced the procedure, the time-dependency has not been verified experimentally.

Later Proposed Procedures

- Limited to 0.5-80 Hz.
- Suitable for any vibration, intermittent vibration, or repeated shock, but not primarily intended for application to single high-magnitude shocks (e.g., >5 *g*).
- Experimental verification of time-dependency is limited to short durations.

General

- Different frequency-weightings available for other axes of vibration.
- Effects of local vibration (hand and feet) should be assessed differently (Ref. 3).
- There is currently no consensus on the relation between any measure of vibration magnitudes and risk or severity of injury.

Key References

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Cross References

10.402 Vibration measurement and representation;

10.428 Effect of vibration magnitude on discomfort;

10.429 Model for predicting the discomfort of seated occupants of vehicles

10.431 Transmission of Vibration Through Seats

Key Terms

Seat transmissibility; whole-body vibration

General Description

A seat often determines the magnitude and type of vibration received by a subject. Seat transmissibility is the transfer function of vertical vibration from the base of the seat to the interface between the seat cushion and the person; it depends upon the dynamics of both the seat and the human body. Seat transmissibility alone is not sufficient to define the usefulness of vibration isolation (CRef. 10.432).

Typical seat-transmissibilities are shown in Fig. 1a. The transmissibility of a perfectly rigid seat is unity at all frequencies. Vibration isolation is achieved if seat-transmissibility resonance frequency is sufficiently below frequencies of dominant energy in the vehicle. It is not possible to greatly reduce the stiffness of a conventional foam and spring seat; a low-stiffness suspension mechanism is required if the resonance frequency is to be reduced to ~1 or 2 Hz. Seat cushions do not greatly affect the transmission of *x*- or *y*-axis vibration (Ref. 2).

Human bodies do not respond like homogeneous rigid masses. Figure 1b shows the driving-point apparent mass of a model of the seated human body (Ref. 3).

Seat transmissibility can be predicted if dynamics of the seat and the person are known (Ref. 3). For example, seat transmissibility is

$$T(\omega) = Z(\omega)/[j\omega A(\omega) + Z(\omega)]$$

where ω is frequency, $A(\omega)$ is the complex driving-point apparent mass of the person, $Z(\omega)$ is the complex mechanical impedance of a massless seat cushion, and j is an imaginary number.

Applications

Seat transmissibilities can be measured with a suitable device between seat cushion and the person (CRef. 10.432). Transfer functions of vibration in other axes, and to other seat-person interface points, can be measured.

Constraints

- Seat transmissibilities illustrated are only typical; they will vary with seats and people.
- Seat transmissibility describes only vertical vibration input at the seat cushion.

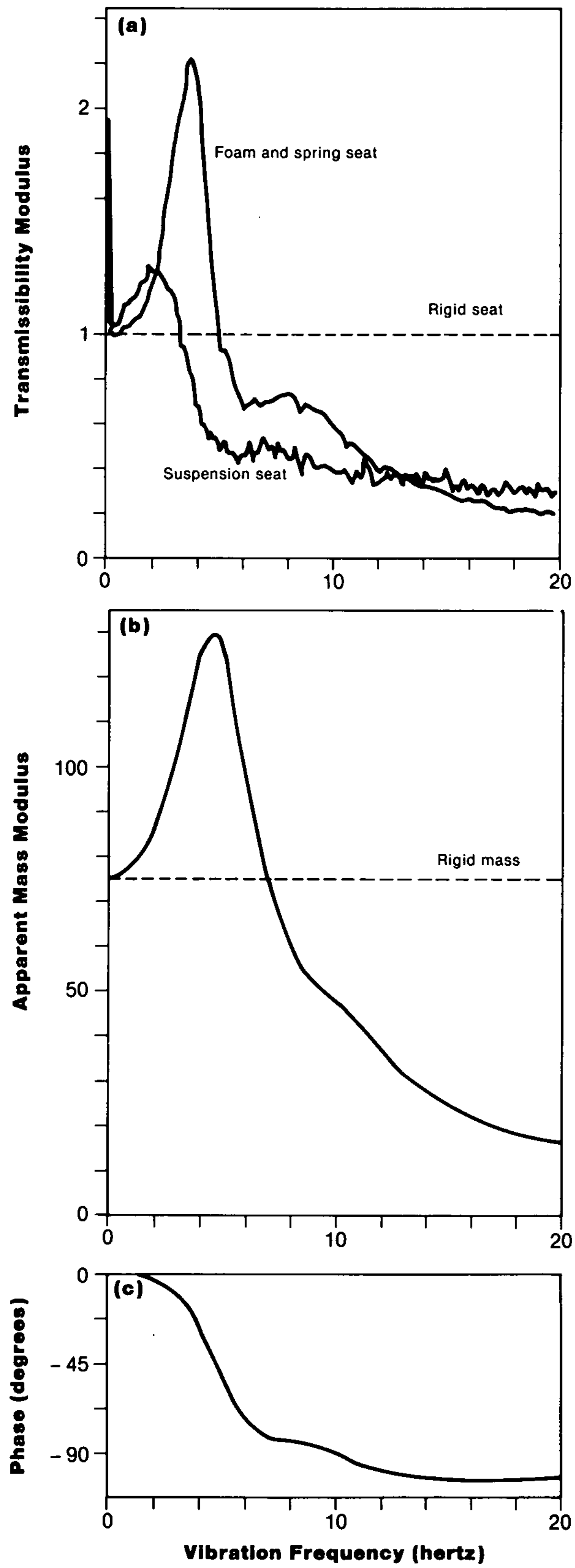

Figure 1. Typical seat transmissibilities (a) and apparent mass modulus (b) and phase (c) of the human body.

Key References

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4. International Organization for Standardization. (1981). *Vibration and shock-mechanical driving point impedance of the human body* (ISO 5982). Geneva: ISO.

Cross References

10.432 Comparison of the vibration isolation effectiveness of seats

10.432 Comparison of the Vibration Isolation Effectiveness of Seats

Key Terms

Seat transmissibility; vibration isolation; whole-body vibration

General Description

The whole-body vibration responsible for performance loss often comes from a seat. Different seats transmit different types and amounts of vibration. Ideally, seats should isolate the human body from vibration, reducing vibration effects on performance, health, and comfort. How well the seat does this is defined by Seat Effective Amplitude Transmissibility (SEAT) (Ref. 1).

The SEAT value is the root mean square (rms) magnitude of the frequency-weighted acceleration at the seat-person interface, expressed as a percentage of rms magnitude of the frequency-weighted acceleration at the seat base. Frequency weighting takes into account relative effects of different frequencies of vibration on the human body. The SEAT value depends upon the frequency-spectrum of seat vibration input (CRefs. 10.403, 10.404, 10.405) and upon seat transmissibility (CRef. 10.431).

Applications

SEAT value is usually concerned with discomfort (CRef. 10.429) produced by vertical vibration, measured at the interface between the seat cushion and the person. It can be applied to vibration inputs in other axes and other points on the seat-person interface, e.g., fore-and-aft vibration on the backrest, and can be used to take into account other effects of the vibration.

Methods

• SEAT % =

$$100\left[\int G_{ss}(f)S^2(f)df\right]^{1/2} \div \left[\int G_{ff}(f)S^2(f)df\right]^{1/2}$$

where $G_{ss}(f)$ is the power-spectrum of acceleration at the seat-person interface, $G_{ff}(f)$ is the power-spectrum of acceleration at the seat base, and $S(f)$ is an appropriate human response to vibration acceleration weighting function.

• Vibration on the seat may be measured with a seat-person interface device, such as an SAE pad (Ref. 2) or **SIT-BAR** (Ref. 3).

• The amount by which the SEAT value is <100% indicates useful seat system vibration isolation.

When SEAT value = 50%, the seat has reduced overall effective vibration to half that of a rigid seat; when SEAT is >100%, seat vibration is worse than vibration at seat input: the seat has increased vibration.

Empirical Validation

It has been extensively validated that weighted rms vibration magnitude is a good measure of discomfort (CRef. 10.429). It has been shown that weighting functions for discomfort obtained with hard, flat seats are applicable to measurements made on soft seats (Ref. 3).

Constraints

• It is assumed that the weighting function correctly takes into account relative effects of different frequencies.

• The procedure applies to continuous vibration and may not be appropriate for impulsive motions.

• SEAT value for vibration input at the seat cushion does not include effects of vibration inputs via the back, feet, thighs, hands, or head.

Key References

1. Griffin, M. J. (1978). The evaluation of vehicle vibration and seats. *Applied Ergonomics*, *9*, 15-21.

2. Society of Automotive Engineers. (1974). *Measurement of whole-body vibration of the seated operator of agricultural equipment* (S.A.E. recommended practice) (SAE J1013) (Handbook Part II, 1409-1417). Warrendale, PA: S.A.E.

3. Whitham, E. M., & Griffin, M. J. (1977). *Measuring vibration on soft seats*. (Paper 770253). Warrendale, PA: Society of Automotive Engineers.

Cross References

10.403 Vibration characteristics of fixed-wing aircraft;

10.404 Vibration characteristics of rotary-wing aircraft;

10.405 Vibration characteristics of on- and off-road vehicles;

10.429 Model for predicting the discomfort of seated occupants of vehicles;

10.431 Transmission of vibration through seats

Notes

10.433 Vibration Exposure Duration: Effect on Visual Performance

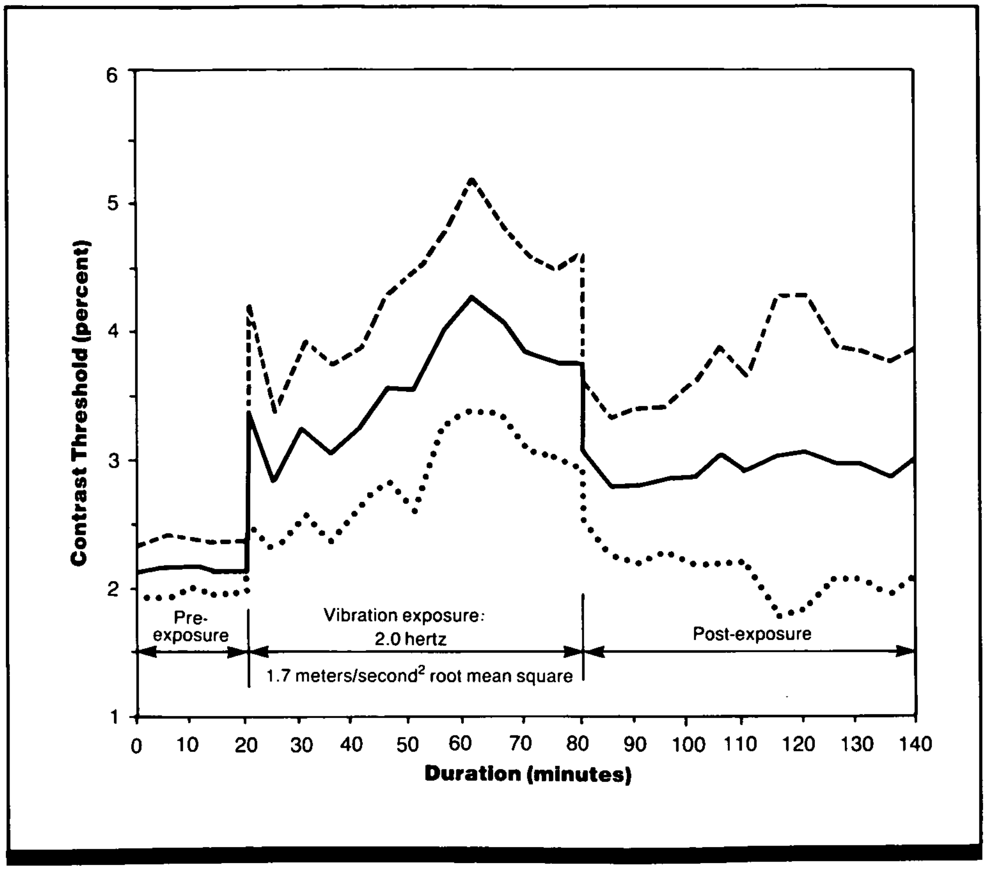

Figure 1. Mean contrast thresholds (solid line) for gratings subtending 12.5 cycles/deg; dashed and dotted lines show ±1 standard deviation. Vibration of observer began after 20 min of visual testing and lasted for 60 min; visual testing continued for 60 min after end of vibration of observer. (Based on Ref. 2)

Key Terms

Contrast sensitivity; head vibration; legibility; vibration duration; vibration exposure; whole-body vibration

General Description

Contrast thresholds for sine-wave gratings subtending 12.5 cycles/deg increase with increasing duration of exposure to whole-body vibration. The reduction in visual performance is correlated with an increase in the magnitude of vertical head vibration.

Applications

Estimating changes in visual performance due to prolonged exposure to vibration.

Methods

Test Conditions

- Horizontally oriented sine-wave gratings subtending 1.5 and 12.5 cycles/deg presented on a display oscilloscope; mean luminance = 3.5 cd/m^2; viewing distance = 0.75 m
- Vibration exposure = 60 min; pre-exposure (static) = 20 min; post-exposure (static) = 60 min
- Vertical vibration (z-axis) presented to observers seated on a rigid flat seat without backrest
- Vibration waveform was sinusoidal, frequency = 20 Hz; acceleration magnitude = 1.7 m/sec^2 root-mean-square
- Monocular viewing

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Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Procedure

- Repeated ascending method of limits
- Independent variables: grating spatial frequency, vibration exposure duration
- Dependent variables: contrast thresholds, magnitude of vertical head vibration
- Observer's task: detect gratings on display oscilloscope at 5-min intervals
- 12 college students and staff, with some practice

Experimental Results

- During exposure to vibration, mean data show a significant trend of increasing contrast thresholds as a function of exposure duration ($p < 0.025$).
- Magnitude of vertical (z-axis) head motion also increases as a function of vibration exposure duration ($p < 0.025$).
- There is no evidence of changes in arousal or motivation during the vibration exposure (no changes in contrast thresholds occur for gratings subtending 1.5 cycles/deg).

Variability

Individual variability in changes of contrast thresholds as a function of time is very large. Reference 2 provides individual subject data.

Repeatability/Comparison with Other Studies

Reference 1 has also demonstrated a time-dependent loss of visual acuity during exposure to whole-body vibration.

Constraints

- Observers were performing a repetitive visual task not typical of all display viewing conditions.

Key References

1. Grzesik, J., Harazin, B., & Pekharsky, M. (1984). The effect of whole-body vibration on vision. Text of paper presented to working meeting: *Criteria of evaluation of effect of whole-body vibration on man* of the Scientific Committee of Physical Factors of the Permanent Commission and International Association on Occupational Health. Meeting held at the Institute of Industrial Hygiene and Occupational Diseases of the USSR Academy of Medical Sciences, 12-16 March.

*2. Moseley, M. J., & Griffin, M. J. (in press). Whole-body vibration and visual performance: An examination of spatial filtering and time-dependency. *Ergonomics*.

Cross References

10.407 Transmission of vertical seat vibration to the head;

10.409 Factors affecting human performance during vibration;

10.416 Display legibility during vibration: effect of luminance contrast;

10.418 Transmission of vibration to the eyes;

10.435 Spatial filtering descriptions of vibration-induced visual disruption

10.434 Vibration Exposure Duration: Effect on Manual Control Performance

Key Terms

Manual control; tracking; vibration exposure; whole-body vibration

General Description

Effects of whole-body vibration on human performance are commonly believed to be time-dependent. Experimental results provide no simple relationship between vibration exposure and task performance. The duration of exposure to vibration has no effect on performance for many tasks. Also, changes in performance over time become smaller with or without vibration when a task (e.g., a continuous manual control task) is performed for an extended duration on more than one occasion (Fig. 1). Similarly, in the same continuous manual control task the proportions of tracking error that relate linearly (input-correlated error) and nonlinearly (remnant) to the movement of the target increase with increasing duration of performance whether or not vibration is present (Fig. 2). The linear parameters of closed-loop human-operator transfer functions may therefore depend upon the task duration.

Applications

Design of manual control systems for performance of extended durations.

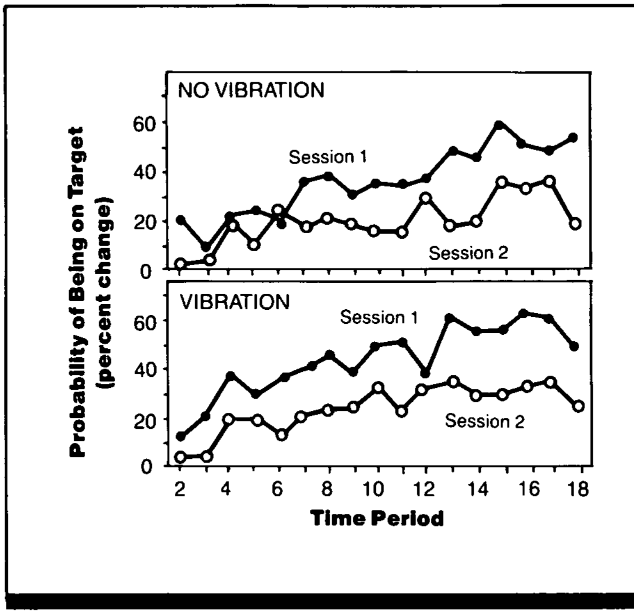

Figure 1. Median percentage change in the probability of being "on" target for two sessions with and two sessions without vibration exposure; percentage of change is for comparison of indicated period with first time period. (Each time period = 11.25 min; Period 18 = post-vibration.) (From Ref. 3)

Methods

Test Conditions

- Observers viewed a stationary display through a collimating lens which placed the display image at optical infinity; observers sat on a wooden seat with an attached thin cushion, back rest, five-point harness, and stationary footrest; observers held a two-axis, isometric (force-type) side-arm control attached to the moving seat frame
- First-order system dynamics; two-axis continuous-pursuit-tracking task
- Forcing functions were integrated Gaussian random time-histories; band-pass filtered with attenuation of 24 dB per octave below 0.01 Hz and 12 dB per octave above 0.2 Hz; independent forcing functions with equal root-mean-square magnitudes for each 11.25-min period and in each axis of the task
- Testing condition was either no vibration or one-octave band random, z-axis, seat vibration centered on 4 Hz at an acceleration magnitude of 1.4 m/sec^2 root-mean-square; vibration was 2.5 times the "fatigue-decreased proficiency" boundary defined in ISO 2631 for 2.5-hr exposures (Ref. 2)

Experimental Procedure

- Between-groups design
- Independent variables: time period (time on task during session), session number, presence or absence of vibration
- Dependent variables: time-on-target, root-mean-square (rms) tracking error, proportion of tracking error linearly correlated with task (input-correlated), proportion of tracking error not linearly correlated with task (remnant), subjective ratings of fatigue and motivation
- Observer's task: use side-arm control to continuously track target
- Observers were highly trained in performing 3-min runs and performed 60 min of continuous tracking prior to the experiment
- Observers performed in two sessions, 1 week apart; in each session, they performed the task for 202.5 min, with 15-sec rests after 11.25 and 191.25 min; vibration exposures started and ended in the two rest periods
- 7 observers in each of two independent groups; one group exposed to vibration on both sessions; other group received no vibration exposure

Experimental Results

- Performance deteriorates with time for all subjects on both sessions.
- Vibration exposure does not significantly alter the time-dependence.
- For both groups of observers, the effect of duration is significantly reduced on the second session compared with the first.
- Increases in total root-mean-square (rms) tracking error with time are accompanied by increases in both input-correlated error and remnant.
- Closed-loop system transfer functions show reductions in moduli and increased phase lags with increasing duration.
- Observer's opinions indicate that performance is disrupted through a combination of fatigue and reduced motivation. Observers feel better prepared for the second session.

Variability

Although the absolute level of performance varied, the effects of duration and session and the changes in input-correlated error and remnant were similar for all subjects.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• The control gain was slightly more sensitive than that found optimal for 3-min exposures and was therefore a cause of fatigue over the extended duration. Control gains should be optimized for the required duration of performance.

• Higher vibration frequencies or magnitudes may produce time-dependent effects.

• The effect of duration may continue to decrease with more than two sessions (Ref. 4).

Key References

1. Griffin, M. J., McLeod, R. W., Moseley, M. J., & Lewis, C. H. *Whole-body vibration and aircrew performance* (I.S.V.R. Technical Report No. 132). Southampton University: Southampton, England.

2. International Standards Organization (1985). *Guide to the evaluation of human response to whole-body vibration* (ISO 2631). Geneva, Switzerland: ISO.

*3. McLeod, R. W., & Griffin, M. J. *Effects of duration on performance of a complex manual control task in a vibration environment*. (In preparation)

4. Seidel, H., Bastek, R., Brauer, B., Buchholz, C., Meister, A., Metz, A. M., & Rothe, R. (1980). On human response to prolonged repeated whole-body vibration. *Ergonomics, 23*, 191-211.

Cross References

9.508 Components of the manual control loop considering the human operator as an element in the control system;

10.421 Model for predicting the effects of vibration on manual control performance;

10.422 Manual control performance: effects of system dynamics and vibration frequency;

10.423 Continuous manual control performance: interactive effects of control gain, control type, and vibration

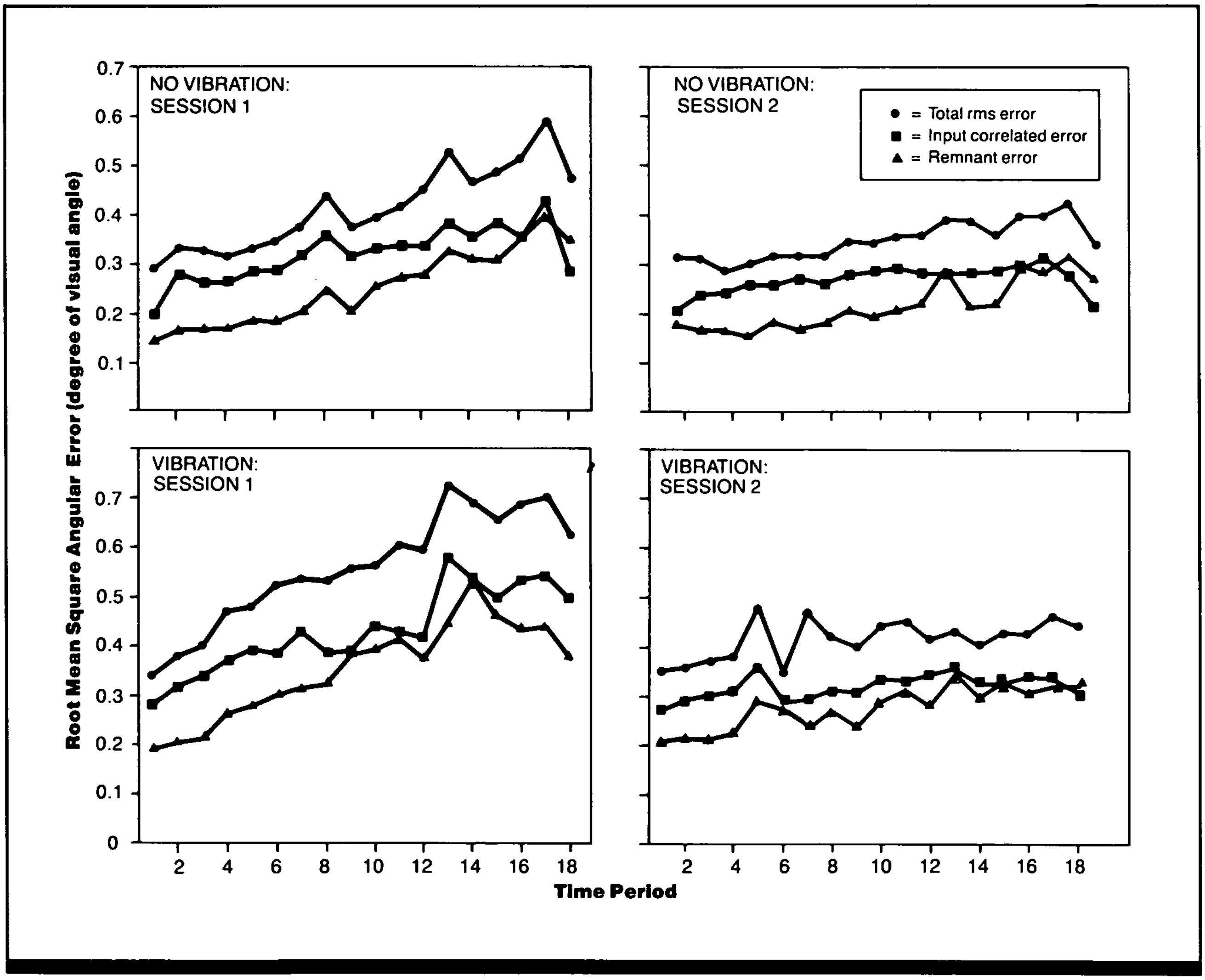

Figure 2. Median RMS angular error and its components in the vertical display axis as a function of time for the same task as Fig. 1. (Each time period = 11.25 min; Period 1 = pre-vibration; Period 18 = post-vibration.) (From Ref. 3)

10.435 Spatial Filtering Descriptions of Vibration-Induced Visual Disruption

Key Terms

Contrast sensitivity; display degradation; legibility; reading error; whole-body vibration

General Description

The degradation of legibility caused by vibration of an observer is predicted by a low-pass spatial filter. Whole-body vertical vibration increases contrast thresholds for sinusoidal grating patterns by an increasing proportion as spatial frequency of the grating increases. In identical vibration conditions, the largest number of reading errors in a reading task occurs with characters that have the largest amounts of high-spatial-frequency information.

Applications

Predicting visual performance and display legibility in environments where vertical vibration may occur.

Methods

Test Conditions

- Sinusoidal grating subtending 7.5, 10, or 12.5 cycles/deg presented on a display oscilloscope; horizontal or vertical orientation, viewing distance of 1.0 m
- 2 x 9 array of numerals in the Huddleston font, each defined by 7 x 9 circular pixels and presented light-on-dark on a monochrome video monitor; symbol luminance = 3.5 cd/m^2; background luminance = 0.1 cd/m^2; angular subtense of characters = 12 min arc of visual angle; vertical spatial complexity of numeric characters defined as "low," "medium," or "high" according to number and separation of illuminated pixels in vertical axis of characters
- Vertical vibration (z-axis) presented to observers seated on a rigid flat seat without backrest
- Sinusoidal vibration frequency = 4 Hz; acceleration magnitude = 2.5 m/sec^2 root-mean-square
- Monocular viewing

Experimental Procedure

- Independent variables: grating spatial frequency, grating orientation, spatial complexity of numeric characters
- Dependent variables: contrast thresholds, reading errors
- Observer's task: detect grating pattern or read as fast and as accurately as possible
- 12 observers, college students and staff, with some practice

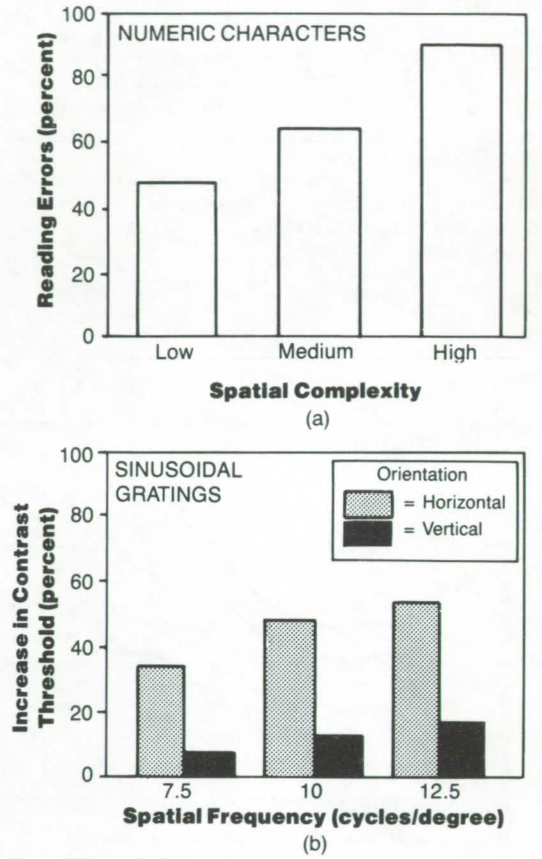

Figure 1. (a) Effect of whole-body vertical vibration on accuracy of reading numeric characters as a function of low, medium, or high character complexity, and (b) effect of the same vibration on contrast threshold for sinusoidal gratings with spatial frequencies of 7.5, 10, and 12.5 cycles/deg. (Based on Ref. 4)

Experimental Results

- Contrast thresholds increase by increasing proportions as the spatial frequency of the grating increases, that is, the increase for 12.5 cycles/deg is proportionally greater than the increase for 7.5 cycles/deg.
- Number of reading errors increases as character spatial complexity increases.
- Significantly greater threshold elevations occur with horizontally oriented gratings (i.e., those orthogonal to the vertical vibration stimulus) than with vertically oriented gratings.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Reference 2 derives a theoretical system modulation transfer function for legibility during vibration that supports the empirical findings shown in Fig. 1.

Constraints

- The extent of display degradation is not only dependent on the spatial frequency characteristics of the visual target but also on the nature of the vibration stimulus (CRef. 10.412) and the parameters of the display (CRefs. 10.413, 10.414, 10.415, 10.416).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Banbury, J. R., Schmit, V. P., Gibson, G. P., & Whitfield, F. B. (1983). *Visual perception of direct view and collimated displays under vibration*. (Tech. Rep. No. 83040). Farnborough, England: Royal Aircraft Establishment.

2. Carel, W. L., Herman, J. A., & Olzak, L. A. (1978). *Design criteria for imaging sensor displays*. (ONR-CR213- 107-1F). Washington, DC: Office of Naval Research. (DTIC No. ADA055411)

3. Evans, D. W. (1980). *The effects of vibration on target acquisition*. Master's thesis, Wright State University, Dayton, OH.

*4. Moseley, M.J., & Griffin, M.J. (in press). Whole-body vibration and visual performance: An examination of spatial filtering and time dependency. *Ergonomics*.

Cross References

1.624 Factors affecting detection of spatial targets;

10.410 Minimum amplitudes of vibration affecting vision;

10.411 Display legibility: effects of vibration frequency;

10.412 Visual performance: effect of random multiple-frequency and multiple-axis vibration;

10.413 Display legibility during vibration: effect of character subtense;

10.414 Display legibility during vibration: effect of character spacing;

10.415 Display legibility during vibration: effect of character font during whole-body vibration;

10.416 Display legibility during vibration: effect of luminance contrast;

10.433 Vibration exposure duration: effect on visual performance

10.501 Glare: Effect on Visibility

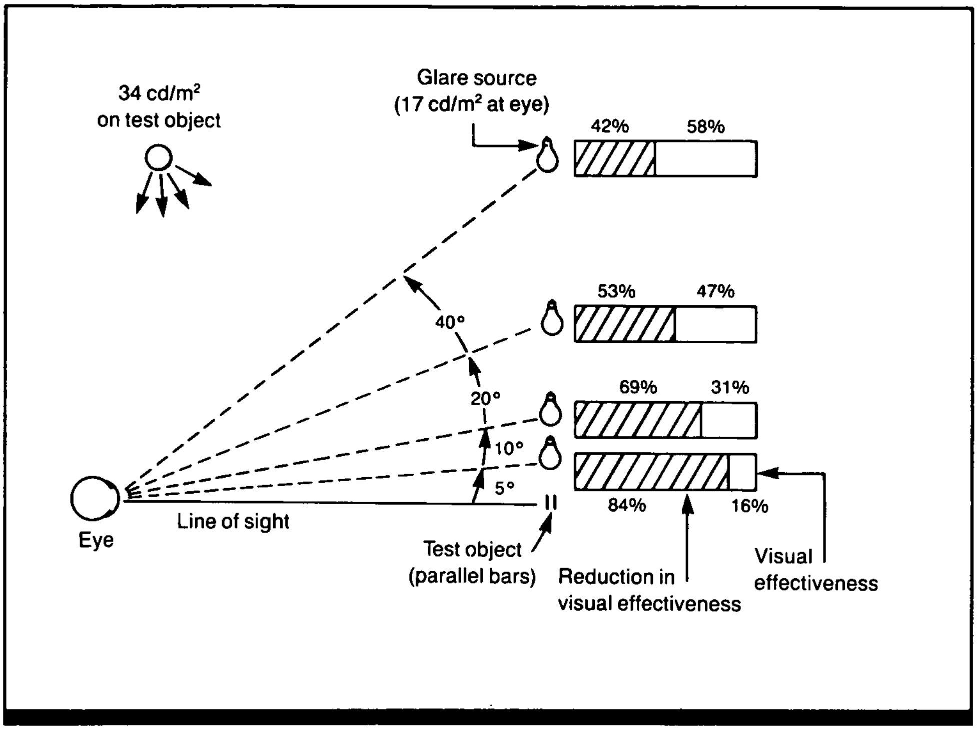

Figure 1. Effect of glare on the amount of light needed to detect a target. The hatched portions of the bars show the reduction in the amount of light required at threshold when the glare is removed (i.e., the reduction in visual effectiveness). (From Ref. 3)

Key Terms

Crew system lighting; glare; image quality; monitoring; search; target acquisition; visual degradation; visual discomfort

General Description

Visibility is decreased by glare: the reduction increases with the luminance of the glare, and is greatest when the source of the glare is in the line of sight.

Applications

Situations in which observers must monitor visual displays in the presence of glare.

Methods

Test Conditions

- Two parallel dark bars of different sizes and contrasts
- White background; luminance 3-300 cd/m^2
- Tungsten bulb glare source with luminance 17 cd/m^2 at the eye

Experimental Procedure

- Method of limits
- Independent variable: angle of glare source from line of sight
- Dependent variables: size and contrast of target at threshold, background intensity required to maintain constant target threshold
- Observer's task: detect the parallel bars
- 9 observers

Experimental Results

- Visibility decreases with proximity of a glare source to the line of sight.

Variability

Between-observer variability was large, but individual differences appeared to be systematic.

Constraints

- Age greatly affects susceptibility to glare.
- The visibility loss due to glare decreases as the ambient illumination increases.

Key References

*1. Cobb, P. W., & Moss, F. K. (1928). Glare and the four fundamental factors in vision. *Transactions of the Illuminating Engineering Society, 23*, 1104-1120.

2. Luckiesh, M. (1944). *Light, vision and seeing*. New York: Van Nostrand.

*3. Luckiesh, M., & Moss, F. K. (1930). The new science of seeing. *Transactions of the Illuminating Engineering Society, 25*, 15-49.

4. Luckiesh, M., & Moss, F. K. (1937). *The science of seeing*. New York: Van Nostrand.

Cross References

1.646 Contrast discrimination;

1.710 Hue and chroma: shifts under daylight and incandescent light;

1.715 Model of brightness contrast;

7.314 Factors affecting monitoring performance;

11.102 Electro-luminescent displays: minimum and preferred symbol luminances;

11.103 Display surround luminance and subjective visual comfort;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.125 Effects on instrument reading performance: pointer, background, and panel lighting colors

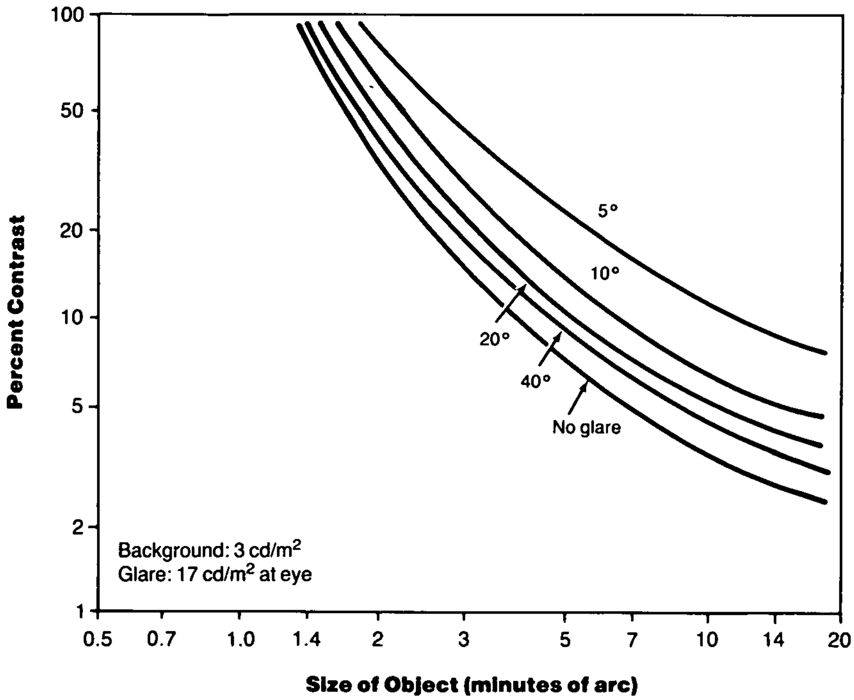

Figure 2. Threshold target contrast for a particular illumination level and background as a function of target size and the angle between the target and a glare source above the target. (From Ref. 1)

10.601 Heat: Effect of Exposure Duration on Task Performance

Key Terms

Attention; cognitive tasks; eye-hand coordination; heat; memory; monitoring; reaction time; sustained attention; temperature sensitivity; tracking; vigilance

General Description

An analysis of 15 studies on the effect of heat suggests an upper limit of exposure above which mental performance is impaired (Fig. 1; also see Ref. 1). Results of a later review of 22 studies suggest that the upper limit for unimpaired mental performance is not well represented by a single line on a graph, due to the large number of variables affecting human performance. A series of isodecrement curves (Fig. 2) describes the relationship between exposure time, temperature, and significant performance changes. Analysis of the isodecrement curves by task category indicates that the temperature-time effects fall into two basic patterns. For reaction-time (RT) tasks and other mental tasks requiring memory and/or speeded decision making (Fig. 2a), increases in both time and temperature increase the likelihood of impaired performance. In contrast, for tracking, vigilance, and complex tasks (all requiring sustained attention), isodecrement curves are primarily dependent on temperature alone (Fig. 2b).

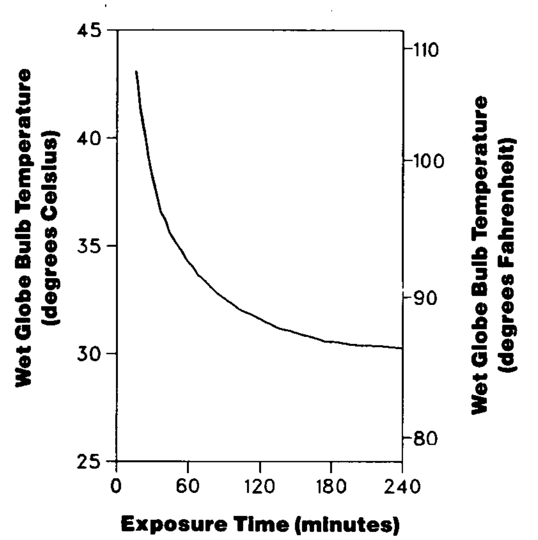

Figure 1. The upper temperature limits for unimpaired mental performance as a function of time. (From Ref. 1)

Methods

Test Conditions

- In the large number of studies analyzed here, the following task types were included (most of them are described in CRef. 10.201); tracking (pursuit and compensatory); reaction time [simple and complex (choice)]; mental tasks (coding, multiplication, mental arithmetic, and short-term memory); vigilance (auditory and visual); complex tasks (several perceptual-motor variations); eye-hand coordination (maze tracing and manual manipulation)
- Exposure time varied from 8-180 min
- Temperature level: 16-43°C (60-110°F)

Experimental Procedure

- Temperature conditions from several studies were converted to an estimated Wet Bulb Globe Temperature (WBGT) index, which indirectly incorporates the psychometric factors of air temperature, humidity, mean radiant heat, and air movement into a single indicator
- Individual discrete data points, defining performance effects at a particular temperature-time combination by a specific researcher, became a data input point for a multiple regression model
- The model generated predictive equations and a series of isodecrement, or equal decrement, curves describing relationships between exposure time, exposure temperature, and the significance of performance changes
- Effects in the predictive models were coded −1 for a performance decrement, 0 if no change in performance was indicated, and +1 for enhanced performance
- Sets of models were developed to describe the relationship for each task category
- Isodecrement curves, representing conditions of increasing likelihood of impaired motor performance, were generated by setting predictive equations equal to decrement levels of 0.0, −0.3, −0.5, −0.8, and −1.0 and then solving, in turn, for temperature and exposure time that represent each of these levels
- 3-6 subjects

Experimental Results

- For reaction time and mental tasks (Fig. 2a), the isodecrement curves superimposed over data points from the literature indicate that increases in either time or temperature increase the likelihood of impaired performance.
- For tracking, vigilance, and complex tasks (Fig. 2b), increased temperature level degrades performance more than does increased exposure time.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The study described here analyzes the results of many more studies and provides a more detailed analysis than does Ref. 1, but for mental work, the two sources are in fair agreement.

Constraints

- The diversity of research findings reported in the literature is a function not only of thermal effects, but also of differences in tasks, experimental conditions, and subject's experience, skill, age, motivation, physical condition, sex, degree of acclimatization, general health, and nutritional state; no summary can take this diversity into account.

Key References

1. NIOSH. (1972). *Criteria for a recommended standard-occupational exposure to hot environments* (USGPO-HSM 72- 10269). Washington, DC: National Institute for Occupational Safety and Health.

2. Ramsey, J. D. (1983). Heat and cold. In. G. R. J. Hockey (Ed.), *Stress and fatigue in human performance* (pp. 33-60). Chichester, England: Wiley.

*3. Ramsey, J. D., & Morrissey, S. J. (1978). Isodecrement curves for task performance in hot environments. *Applied Ergonomics,* 9, 66-72.

Cross References

7.314 Factors affecting monitoring performance;

10.201 Types of tasks used in measuring the effects of stress, fatigue, and environmental factors on performance;

10.202 Effects of different stressors on performance;

10.702 Circadian variation in body temperature;

Handbook of perception and human performance, Ch. 44, Sect. 3.2

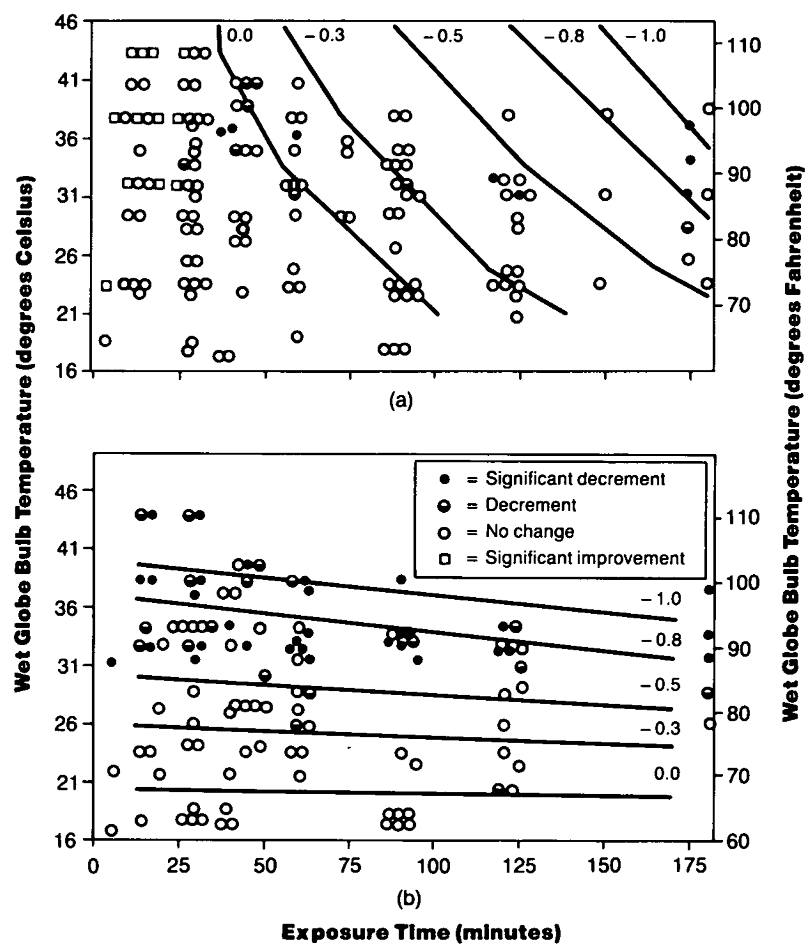

Figure 2. Temperature-time effects on (a) mental reaction time performance and (b) combined tracking, vigilance, and complex tasks. The 0 decrement curve represents the boundary for unimpaired performance, the −1 curve represents the boundary for significant decrements in performance, and intermediate curves are associated with increasing likelihood of performance decrements. (From Ref. 3)

10. 602 Cold: Effect on Performance

Key Terms

Cold; manual dexterity; reaction time; temperature sensitivity

General Description

The thermal environment can be a stressor and can affect human performance. The effects of a cold environment can sometimes be offset by additional clothing. The amount of insulation added to the hands markedly affects manual dexterity, a common measure of performance. Extreme cold has less effect on body temperature and on performance than cold coupled with high wind velocity, as measured by the windchill index. In contrast to the usually detrimental effects of extreme cold, coolness (temperatures within but at the lower end of the human comfort range) can improve performance on some tasks. The table summarizes the effect of cold temperatures on performance.

Constraints

- Where mental effect is measured by a manual response like key pressing or writing, the effect of cold on mental performance may be confounded with the effect of cold on manual dexterity.
- In addition to acclimatization (or lack of it), reaction to thermal stress can be affected by other stressors, by psychological factors of expectancy and will, and by diet. The most negative effects of cold on psychomotor performance were demonstrated by those on a high protein diet, the least by those on a high fat diet, and intermediate by those on a high carbohydrate diet (Ref. 9).

Key References

1. Bensel, C. K., & Lockhart, J. M. (1974). Cold-induced vasodilation onset and manual performance in the cold. *Ergonomics*, 17, 717-730.

2. Clark, R. E., & Cohen, A. I. (1960). Manual performance as a function of rate of change in hand-skin temperature. *Journal of Applied Physiology, 15*, 496.

3. Dusek, E. R. (1957). Effect of temperature on mental performance. In *Protection and functioning of the head in cold climates*. Washington, D. C.: National Academy of Sciences, National Research Council.

4. Gaydos, H. F., & Dusek, E. R. (1957). Effects of localized hand cooling versus total body cooling on manual performance. *Journal of Applied Physiology, 12*, 377-380.

5. Holmberg, I., & Wyon, D. P. (1969). The dependence of performance in school on classroom temperature. *Educational and Psychological Interactions, 31*, 1-20.

6. Horvath, S. M., & Freedman, A. (1947). The influence of cold upon the efficiency of man. *Journal of Aviation Medicine, 18*, 158-164.

7. Lockhart, J. M. (1966). Effects of body and hand cooling on complex manual performance. *Journal of Applied Psychology, 50*, 57-59.

8. Lockhart, J. M., Kiess, H. O., & Clegg, T. J. (1975). Effect of rate and level of lowered finger surface temperature on manual performance. *Journal of Applied Psychology, 60*, 106-113.

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10. Poulton, E. C., Hitchings, N. B., & Brooke, R. B. (1965). Effect of cold and rain upon the vigilance of lookouts. *Ergonomics*, 8, 163-168.

11. Provins, K. A., & Clarke, R. S. J. (1960). The effect of cold on manual performance. *Journal of Occupational Medicine, 2*, 169-176.

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14. Teichner, W. H. (1958). Reaction time in the cold. *Journal of Applied Psychology, 42*, 54-59.

15. Teichner, W. H., & Kobrick, J. L. (1955). Effects of prolonged exposure to low temperature on visual-motor performance. *Journal of Experimental Psychology, 49*, 122-126.

16. Teichner, W. H., & Wehrkamp, R. F. (1954). Visual-motor performance as a function of short duration ambient temperature. *Journal of Experimental Psychology, 47*, 447-450.

17. Wyon, D. P. (1973). *The effects of moderate heat stress on typewriting performance*. Paper presented at the International Symposium on Quantitative Prediction of Effects of Thermal Environment on Man, Strasbourg, France.

Cross References

9.101 Reaction time tasks and variability;

10.601 Heat: effect of exposure duration on task performance;

10.711 Circadian variation in vigilance performance and body temperature for individuals with different work shift preferences

Cold Condition	Effect on Performance	Source
Hand-skin temperature lowered to 11.5°C (53.7°F)	Significant decrement in manual dexterity	Ref. 4
Hand-skin temperature kept at 27°C (80.6°F) but body surface cooled	No decrement	Ref. 4
Whole body exposed to cold	Greatest decrement in six manual dexterity tasks observed at faster rates of cooling	Ref. 1
Four conditions: 1. body and hand warm 2. body cold and hand warm 3. body warm and hand cold 4. body and hand cold	Over conditions 1-4, performance on complex manual tasks deteriorates	Ref. 7
Body warm, hands in cold box	Greater loss in performance of knot tying with slow cooling rates	Ref. 2
Finger temperature of 6°C (42.8°F)	Minimum temperature at which tactual discrimination sensitivity is not impaired	Ref. 11
Finger temperature below 15.6°C (60°F)	Significant decrement in manipulative performance	Ref. 3
Finger temperature below 10°C (50°F)	Onset of pain produces extensive loss of manual abilities	Ref. 3
Finger temperature below 4.4°C (40°F)	Touch discrimination is lost, as is the ability to perform fine manipulative movement	Ref. 3
Subjects in −30°C (−20°F) room for 2 weeks	Significant decrement on manipulation task and writing; no effect on a code test or on visual performance	Ref. 6
Subjects with surface temperature of 9-18°C (48-64°F)	Performance on all manual tasks decreased with lowered temperature	Ref. 8
Lowered body temperature on-board ship in Arctic	Significant delay and inaccuracy in watch-keeping tasks as body temperature falls	Ref. 10
Subjects in 13°C (55°F) or 24°C (75°F) room	At lower temperature, impaired in pursuit tracking and less sensitivity to radiant heat pain	Ref. 15
Environments of 13°C (55°F), 21°C (70°F), 30°C (85°F), and 38°C (100°F)	Performance decrement on tracking tasks both above and below 21°C (70°F)	Ref. 16
Temperature at −37°C (−34.6°F) in still air	Reaction time not significantly affected	Ref. 14
Temperature at −37°C (−34.6°F) with increased wind speed	Greatly increased reaction time	Ref. 14
Temperature of 20-24°C (68-75°F) for several hours	Cooler temperature produced better typing performance	Ref. 17
Classroom at 20-30°C (69-86°F)	Reading speed and comprehension deteriorated 30% at higher temperature	Ref. 5
Temperature at 29°C (84°F), 25.6°C (78°F), or 20°C (68°F)	Best performance on two of four perceptual-motor tasks obtained at 20°C	Ref. 13

10.701 Characteristics of Biological Rhythms

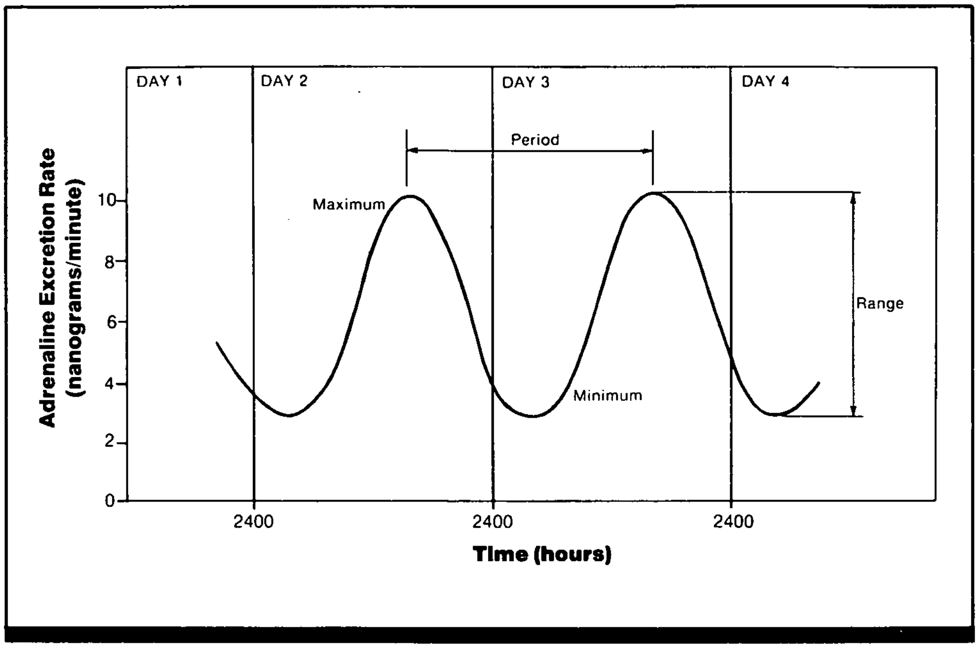

Figure 1. Idealized example of sinusoidal rhythm based on the excretion of adrenaline in urine over four days. (From *Handbook of perception and human performance*)

Key Terms

Chronobiology; circadian rhythm; endogenous rhythms; entrained rhythms; exogenous rhythms; infradian rhythms; periodicity; ultradian rhythm

General Description

Chronobiology is the study of biological rhythms. Human rhythms oscillate at frequencies from once a fraction of a second to once a year. The environmental condition which has the greatest effect on human rhythms is the solar day, with its frequency of once per 24 hr. A rhythm can be defined as a sequence of events, repeating themselves through time, in the same order and at the same interval. A biological rhythm, however, may vary in some of its characteristics, for instance, amplitude, phase, or period.

The *period* of a biological rhythm (the reciprocal of its frequency) is the time to complete one cycle. Circadian rhythms have a period of ~24 hr (20-28 hr), e.g., body temperature. Rhythms with a period less than 24 hours, such as respiration, are ultradian rhythms; those with a longer period, such as menstruation, are infradian rhythms.

The *mean* or *level* of a rhythm is the average value of a continuous variable over a single cycle. When the rhythm is described by fitting of a cosine curve, the average or level of the best-fitting cosine curve is the mesor, which equals the arithmetic mean only when the data are measured equidistantly and over an integral number of cycles.

The *amplitude* of the rhythm refers to the magnitude of the variable between its mean value and the trough or peak, but such a definition is limited to only those biological rhythms that oscillate symmetrically about the mean level. Amplitude is sometimes used to designate the range (see Fig. 1) of oscillation from peak to trough.

The phase of the rhythm, in its strictest definition, is the instantaneous state of the rhythm within a cycle (i.e., position of rhythm in time) represented by a value of the variable, for example, the maximum or minimum. In biological rhythms, phase may refer to the location of the peak relative to some arbitrary fixed time point, such as midnight (2400 hr). Where data are represented by a fitted cosine curve, the phase of the rhythm may be defined by the acrophase, the time at which the cosine function reaches its maximum. Phase also defines the temporal relation between two rhythms where similar aspects of both occur simultaneously; the opposite, where the maximum of one occurs simultaneously with the minimum of the other, is the antiphase.

A *phase shift* is displacement in either direction along the time axis of a rhythm which retains its original shape. For example, a phase-delay, perhaps caused by a westward flight through several time zones, means that every point in the rhythm occurs somewhat later, while a phase-advance, caused by eastward flight, means that every point occurs earlier.

If the capacity for rhythmic change is seen as an inherent characteristic of living organisms, then an internal, self-sustaining oscillator must produce these *endogenous*

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

rhythms. Often rhythms are measured in individuals exposed to the night-and-day influences of the solar day, which include light/dark cycles, environmental temperature changes, and rhythms of social behavior. A rhythm, such as that of periodically emptying the bladder, which may be determined by the social behavior of eating and drinking during the day and fasting at night, may appear to be exogenously caused. Such a rhythm, however, may actually be an endogenous rhythm driven by an internal oscillator, but not completely independent of the periodicity of a night-and-day environment. When the internal clock is synchronized to a 24-hr periodicity by environmental influences called *zeitgebers*, it is considered entrained. Exogenous rhythms, driven by external influences, can easily be changed in phase or period, whereas endogenous rhythms are more difficult to influence.

To determine whether a rhythm is endogenous, environmental influences can be experimentally controlled by isolating subjects in caves, in polar regions, or in carefully constructed isolation units where even a slight increase in vibration of the building during heavy daytime traffic in the streets outside is controlled. Schedules which manipulate day and night conditions may alter perception of time by suddenly changing the period or phase of a *zeitgeber*, by producing abrupt time shifts, by establishing routine non-24-hr days, or by maintaining consistent conditions with no *zeitgebers*, producing a free-running rhythm. Efforts to produce desychronization of the external environment and biological rhythms are called free-running experiments.

If all internal rhythms synchronize with the periodicity of the free-running sleep/wake cycle, the endogenous nature of those rhythms cannot be demonstrated. Two free-running rhythms with different periods are endogenous only if internal desynchronization occurs. Endogenous rhythms have been established for body temperature and the sleep/wake cycle, but since individuals eat while they are awake and not while they are asleep, many other rhythms may have separate endogenous components that are masked by other influences.

Constraints

- In establishing that a periodicity exists, patterns of measurement are crucial.

Key References

1. Halberg, F., Caradente, F., Cornelissen, G., & Katinas, G. S. (1977). Glossary of chronobiology. *Chronobiologia, 4* (Suppl. 1), 1-189.

*2. Minors, D. S., & Waterhouse, J. M. (1981). *Ciradian rhythms and the human*. Bristol: John Wright and Sons.

3. Monk, T. M., & Leng, V. C. (1982). Time of day effects in simple repetitive tasks: Some possible mechanisms. *Acta Psychologica, 51*, 207-221.

4. Monk, T. H., Fookson, J. E., Kream, J., Moline, M. L., Pollack, C. P., & Weitzman, M. B. (1985). Circadian factors during sustained performance: Background and methodology. *Behavior Research Methods, Instruments, & Computers, 17*, 19-26.

5. Naitoh, P., England, C. E., & Ryman, D. H. (1985). Circadian rhythms determined by cosine curve rhythm: Analysis of continuous work and sleep-loss data. *Behavior Research Methods, Instruments, & Computers, 17*, 630-641.

6. Sing, H. C., Thorne, D R., & Hegge, F. W. (1985). Trend and rhythm analysis of time-series data using complex demodulation. *Behavior Research Methods, Instruments, & Computers, 17*, 623-629.

Cross References

10.702 Circadian variation in body temperature;

10.703 Cyclical patterns of sleep;

10.704 Time of day: effect on memory;

10.705 Time of day: effect on short-term memory and speeded decision making;

10.706 Time of day: effect on speeded decision making;

10.707 Circadian variation in work efficiency;

10.708 Incentive and introverted/extroverted personality: effects on the diurnal rhythm of performance;

10.710 Adaptation of circadian rhythms to altered schedules;

10.711 Circadian variation in vigilance performance and body temperature for individuals with different work shift preferences;

10.712 Schedule shift: effect on performance;

10.713 Rapid time-zone shifts: effect on performance and body temperature;

10.808 Sleep deprivation: effect on circadian rhythm;

Handbook of perception and human performance, Ch. 44, Sect. 4.2

10.702 Circadian Variation in Body Temperature

Key Terms

Body temperature; circadian rhythm; diurnal variation; heat loss

General Description

Fluctuation in core body temperature (BT) throughout the day (circadian rhythm) for male subjects resting in the nude in an ambient temperature of 32°C (upper curve, Fig. 1) is similar to the BT rhythm for men who went about their normal work schedule (lower curve, Fig. 1). These data illustrate the stability of the BT rhythm under disparate conditions of exercise or rest. The small difference (~0.3°C) in the mean temperature levels of the two groups is probably an artifact, reflecting two methods of measurement: rectally for resting subjects, and sublingually (under the tongue) for working subjects.

The central factor in the regulation of body core temperature is variation in heat conductance. Conductance is a coefficient which represents mean heat flux through the skin surface per degree of gradient fall between core and skin temperature. The diurnal cycle of variation in conductance is illustrated in Fig. 2. In resting subjects about 75% of the variation in BT over a 24-hr period is due to heat loss through conductance and only 25% to heat production through metabolism. The amplitude (or range) of the BT rhythm is influenced by the effect of the ambient temperature on conductance (Fig. 3).

Applications

Since performance is known to slightly lag BT in phase and to be positively correlated with it, then critical work tasks should be scheduled, if possible, during the period when the circadian cycle of BT is rising or at its peak and avoided as the cycle turns downward or is at its trough.

Methods

Test Conditions

- Unclothed subjects rested in climatic chamber continuously for 27 hr; dressed subjects performed their normal work routine; BT measured by rectal probe or sublingually; heat flow measured by small gradient calorimeters, consisting of round Plexiglas discs (diameter, 8 mm) attached to 11 points on the skin surface; skin temperature recorded at each disc location
- Ambient temperatures of 20, 24, 28, and 32°C; relative humidity 40-50%
- Subjects consumed equal amounts of water and glucose at hourly intervals

Experimental Procedure

- Independent variables: resting or working conditions, ambient temperature, time of day (during 27-hr period), rectal or sublingual probe
- Dependent variables: BT, skin temperature, overall conductance, conductance at extremities and trunk
- 9 male subjects for rectal probe measurement; 73 males (naval personnel) for sublingual probe measurement

Experimental Results

- Skin temperature and heat conductance decrease in the daytime, but increase steeply, beginning at ~1900 hr (shown for ambient temperature of 20°C in Fig. 2).
- The increase in heat conductance precedes the characteristic fall in BT by ~2 hr (Fig. 2).

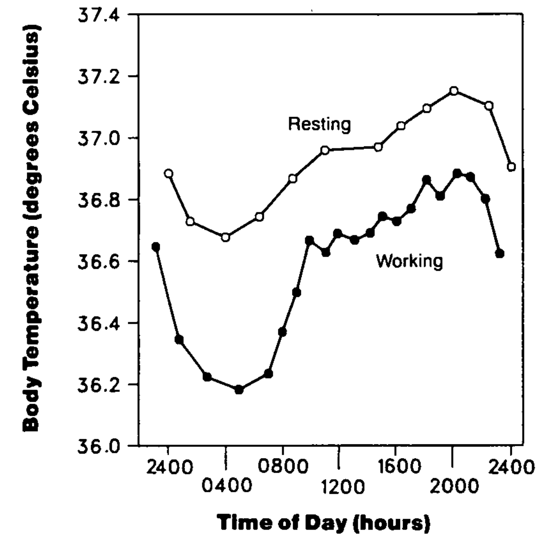

Figure 1. Body temperature as a function of time of day for resting (Ref. 1) and working (Ref. 2) subjects measured by rectal or sublingual probes, respectively. (From *Handbook of perception and human performance*)

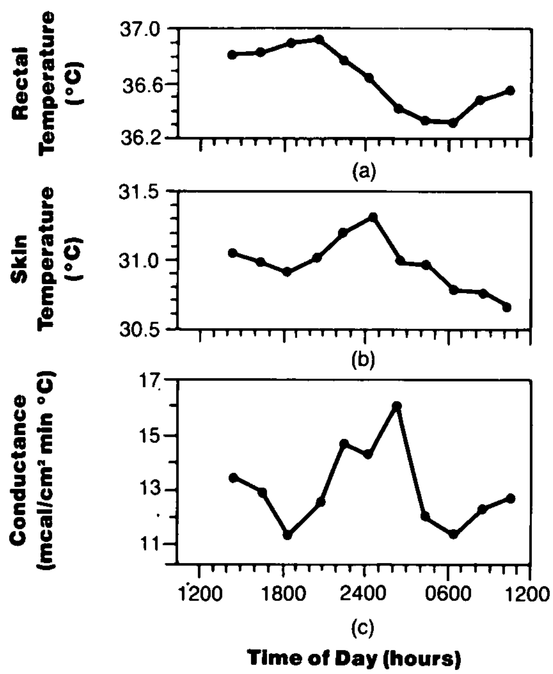

Figure 2. (a) Rectal temperature, (b) mean skin temperature, and (c) internal conductance (core to skin), as a function of time of day. (From Ref. 1)

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• The range of the diurnal oscillation measured between maximal and minimal values is 0.64°C for rectal temperature, 0.60°C for mean skin temperature, and 5 mcal/cm^2 min/°C for conductance.
• The mean value of conductance (for 24 hr) is 13.0 mcal/cm^2 min °C for an ambient temperature of 20°C.
• Averaged conductance is 5.8% higher during early night (1800-2400 hr) than in the morning (0600-1200).
• Differences in conductance between the trunk and the distal extremities depend on ambient temperature: trunk conductance is nearly unchanged between 20 and 32°C, whereas conductance of hands and feet changes by 90% over the same ambient temperature range.
• The range of oscillation of BT depends systematically on ambient temperature (shown for 4 subjects in Fig. 3), being largest at 24°C and smallest at 32 or 20°C.

Variability

Data for individual subjects is shown in Fig. 3. No other information on variability was given.

Repeatability/Comparison with Other Studies

The stability of BT circadian rhythm has been shown in the free-running situation (CRef. 10.714). The slow adaptation of body temperature after jet travel (CRef. 10.713) and switch to shift work tends to confirm the stability of the BT rhythm.

Constraints

• Metabolism may play a greater role in circadian variation in the normal condition of eating large meals than it does in these resting, once-an-hour feeding conditions.

Key References

*1. Aschoff, J., & Heise, A. (1972). Thermal conductance in man: Its dependence on time of day and ambient temperature. In S. Itoh, K. Ogata, & H. Yoshimura (Eds.), *Advances in climatic physiology* (pp. 334-348). Tokyo: Igaku Shoin.

*2. Colquhoun, W.P. (1971). *Biological rhythms and human performance*. London: Academic Press.

Cross References

10.701 Characteristics of biological rhythms;

10.710 Adaptation of circadian rhythms to altered schedules;

10.713 Rapid time-zone shifts: effect on performance and body temperature;

10.714 Sleep/wake and body temperature cycles during isolation from external time references;

Handbook of perception and human performance, Ch. 44, Sect. 4.2

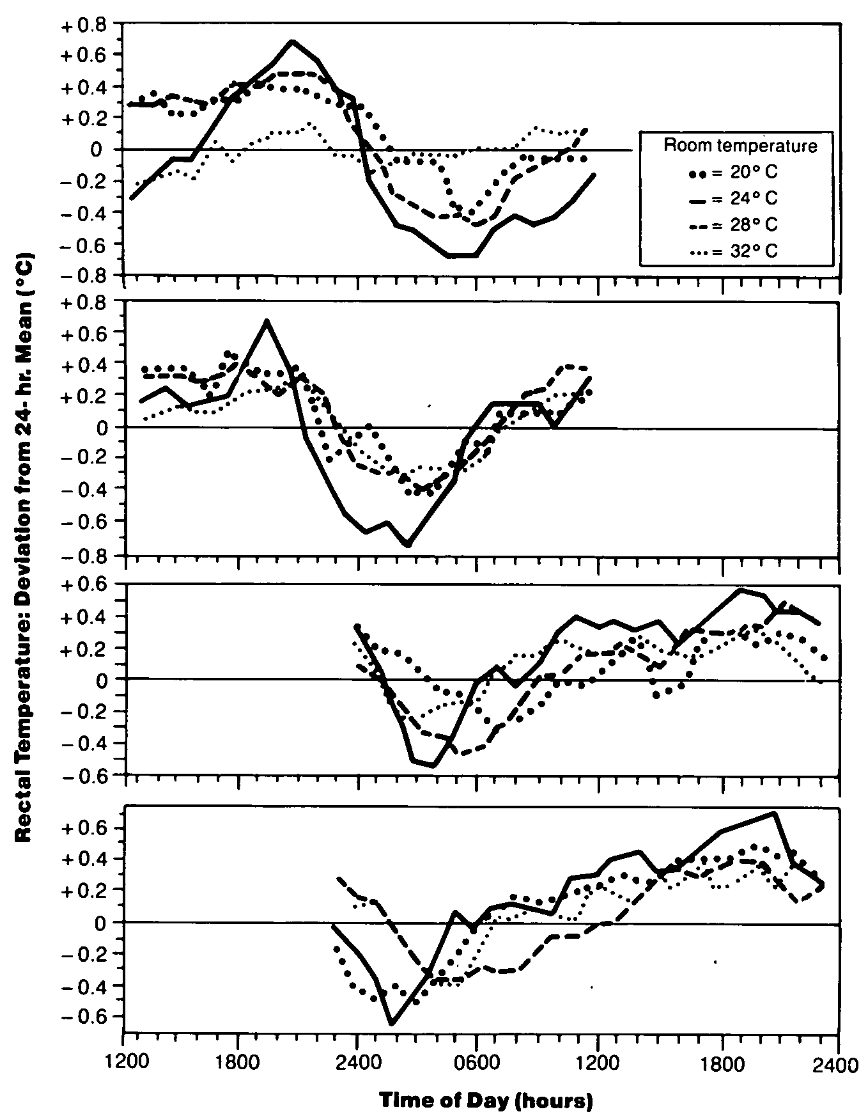

Figure 3. Rectal temperature of 4 resting subjects as a function of time of day; temperatures measured at four ambient temperatures. (From Ref. 1)

10.703 Cyclical Patterns of Sleep

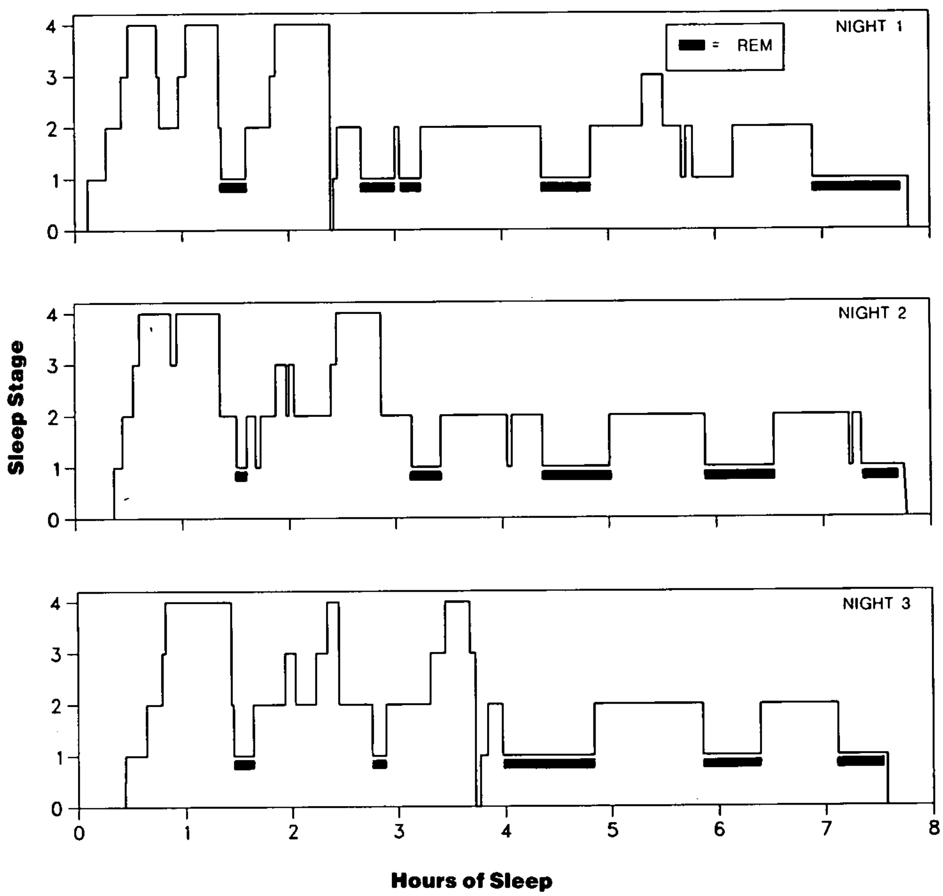

Figure 1. The pattern of sleep (EEG) across the night: sleep stage as a function of hours of sleep for one subject tested on three consecutive nights. (From Ref. 4)

Key Terms

Circadian rhythm; rapid eye movements; sleep; ultradian rhythm

General Description

For a normal, human's nightly sleep of 7.5- or 8-hr, there is a rhythm of shorter periodicity (ultradian rhythm) than the circadian. Although this periodicity is highly variable across subjects, it has an approximate mean value of 90 min. As an individual passes from waking (Stage 0, Fig. 1) to heavy sleep (Stage 4), the electroencephalogram (EEG) shows increased synchrony, higher voltage (caused by the synchrony), and lower-frequency patterns (from 13-30 to 1-4 Hz). Within each of the four or five such cycles occurring in one night's sleep is a period of rapid eye movement (REM) (black bars in Fig. 1) associated with dreaming.

Methods

- Subject spent several nights in a sleep research laboratory; comfortable sleeping cubicle
- Wires from electrodes for EEG, electromyogram (EMG), and electroculogram (EOG) gathered into a bundle that plugged into wall at head of bed, so that the instruments could be monitored outside the cubicle

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- First night's sleep (top panel, Fig. 1) is considered atypical, probably due to the unusual situation.
- EEGs of waking, alert, aroused, excited, or problem-solving subject are characterized by desynchronous, irregular, low-voltage, high-frequency (13-30 Hz) beta activity.
- When subject is quietly resting with eyes closed, alpha waves (regular, high-voltage, low-frequency, 8-12 Hz, pattern) dominate.
- Alpha waves are soon replaced by Stage 1 sleep. Ten min later, subject enters Stage 2, followed 15 min later by a few delta waves (1-4 Hz) signaling entry into Stage 3. Over next 15 min, delta waves predominate (Stage 4). Together, Stages 3 and 4 are called slow wave sleep (SWS).
- About 90 min after the onset of sleep, an abrupt change occurs: the EEG becomes desynchronous (because it shows a waking beta pattern, this stage is sometimes called paradoxical sleep); EOG shows that the eyes are darting rapidly back and forth (rapid eye movement or REM); EMG becomes silent due to a profound loss of muscle tonus and paralysis (a massive inhibition of alpha motor neurons); and cerebral blood flow and oxygen consumption are accelerated.
- During remainder of night, SWS and REM alternate, each cycle lasting ~90 min, containing 20-30 min of REM.
- SWS, especially Stage 4, is accomplished early in the night. The amount of SWS in a night's sleep can be increased by lengthening the time between sleep periods (implying the SWS is necessary for bodily recovery from fatigue, Ref. 2). Awakened from SWS, subject reports not dreaming, but may report the presence of a thought, an image, or some emotion.
- REM is accomplished later in the night. The amount of REM in a night's cycle can be increased by selective deprivation of sleep stage, on the previous night (REM rebound) or by adjusting sleep time to morning hours (implying that REM is coordinated by time of day, Ref. 2). Awakened at this stage, subject usually reports action or narrative type of dream.

Variability

Although length of cycle varies among subjects, all subjects show ultradian cycles within the night's sleep, and cycle length is reliable across nights for a given subject.

Repeatability/Comparison with Other Studies

Many sleep researchers report similar cycles of sleep stages.

Constraints

- SWS does not seem to be related to dreams in the way that REM is, but it often correlates with instances of sleepwalking, bed-wetting, and severe nightmares (night terrors).

Key References

1. Carlson, N. R. (1977). *Physiology of behavior*. Boston: Allyn and Bacon.

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Cross References

10.701 Characteristics of biological rhythms;

10.702 Circadian variation in body temperature;

10.709 Ultradian rhythms;

10.710 Adaptation of circadian rhythms to altered schedules;

10.714 Sleep/wake and body temperature cycles during isolation from external time references;

10.809 Partial deprivation of sleep: effect on performance;

10.810 Selective sleep deprivation: effect on memory;

Handbook of perception and human performance, Ch. 44, Sect. 3.5

10.704 Time of Day: Effect on Memory

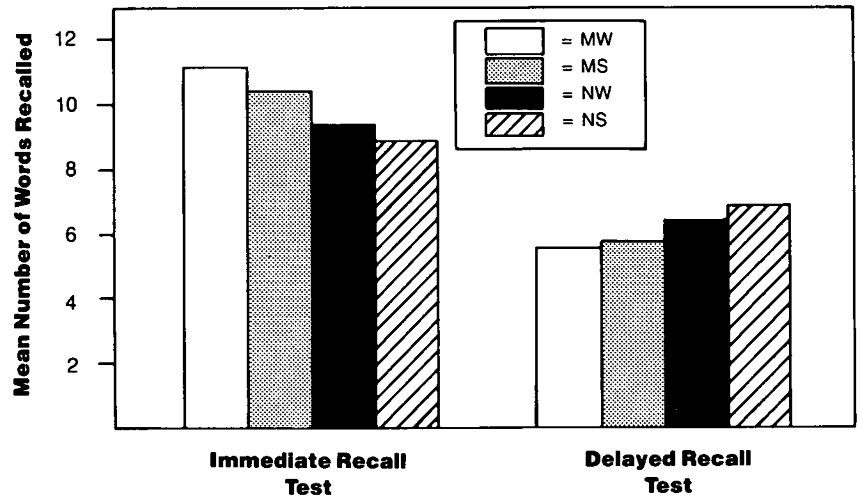

Figure 1. Mean number of words recalled at initial test and retest 5 hr later. M = morning learning, N = night learning, W = awake during test-retest interval, S = asleep during same interval. (Adapted from Ref. 2)

Key Terms

Body temperature; circadian rhythm; diurnal variation; memory; time of day

General Description

The diurnal rhythm for performance on memory tasks appears to differ from the performance rhythm for other types of tasks. Whereas performance on most tasks follows the body temperature rhythm and improves steadily through the day, memory performance may be better in the morning. Time of day clearly affects immediate recall (short-term memory), with material presented in the morning recalled better than material presented later in the day. For delayed recall (long-term memory), sleep/wake and time of day are usually confounded. For subjects who learn a list of words late in the evening or early in the morning and then sleep or remain awake for 5 hours before the retest, evening presentation appears to enhance long-term memory, while morning presentation enhances short-term memory.

Methods

Test Conditions

- List of 30 common bisyllabic nouns presented at rate of one word every 2 sec on tape; order of words varied randomly for each subgroup of 2-3 subjects, balanced across conditions
- Word presentation, initial test, intervening activity, and retest took place in the morning (M) or night (N); subjects slept (S) or were awake (W) during the test-retest interval
- Presentation of word list and initial test at 2300 hr for night groups (N) or 0630 hr for morning groups (M); retest at 0400 (N) or 1130 (M)
- After initial test, S (sleep groups) went to bed; W (waking groups) read, talked, and played games until retest; subjects were told they would be given another test in 5 hr, but were led to believe it would be a different kind from the first (to preclude rehearsal)

Experimental Procedure

- Between-groups factorial design
- Independent variables: time of list presentation and immediate recall test (2300 or 0630 hr), time of delayed recall test (0400 or 1130 hr), condition during 5-hr test-retest interval (awake or asleep)
- Dependent variables: number of words recalled on each test, percentage lost between tests
- Subject's task: recall in writing as many list words as possible
- 10 female undergraduates with normal sleeping habits in each of four groups

Experimental Results

- The mean scores for the immediate recall test are higher for the combined morning groups than for the night groups ($p<0.02$) (Fig. 1).
- Time of day significantly affects the percentage of loss between tests ($p<0.001$). Percentage loss on the delayed recall test is greater for the morning groups than for the night groups.
- Neither the sleeping/waking condition nor the interaction between time of day and sleeping conditions is significant.

Variability

Significance was determined by pooled *t*-test and analysis of variance.

Repeatability/Comparison with Other Studies

Digit span test performance peaks in the morning (Ref. 1).

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Constraints

- Night sleep and morning sleep may contribute differently to memory consolidation (Ref. 3).
- The partial design used here omits control groups: (a) sleeping before the two night conditions, and (b) awake before the two day conditions. Although the present design eliminates the confound of time of day and sleep from the long-term memory data, it does not exclude the effect of fatigue on short-term memory.

Key References

1. Blake, M. J. F. (1967). Time of day effects in performance in range of tasks. *Psychonomic Science, 9,* 349-350.

*2. Hockey, G. R. J., Davies, S., & Gray, M. M. (1972). Forgetting as a function of sleep at different times of day. *Quarterly Journal of Experimental Psychology, 24,* 386-393.

3. Yaroush, R., Sullivan, M. J., & Ekstrand, B. R. (1971). Effect of sleep on memory. II: Differential effect of the first and second half of the night. *Journal of Experimental Psychology, 88,* 361-366.

Cross References

10.601 Heat: effect of exposure duration on task performance;

10.702 Circadian variation in body temperature;

10.705 Time of day: effect on short-term memory and speeded decision making;

10.706 Time of day: effect on speeded decision making;

10.809 Partial deprivation of sleep: effect of performance;

10.810 Selective sleep deprivation: effect on memory;

10.811 Partial sleep deprivation: effect on vigilance and cognitive performance

10.705 Time of Day: Effect on Short-Term Memory and Speeded Decision Making

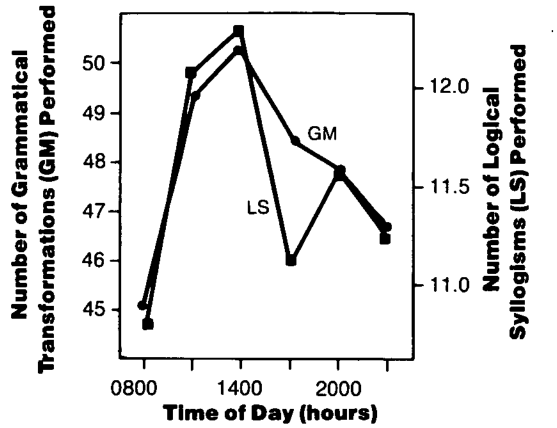

Figure 1. Number of items completed on the grammatical transformation (GM) and logical syllogism (LS) tasks as a function of time of day. (From Ref. 3)

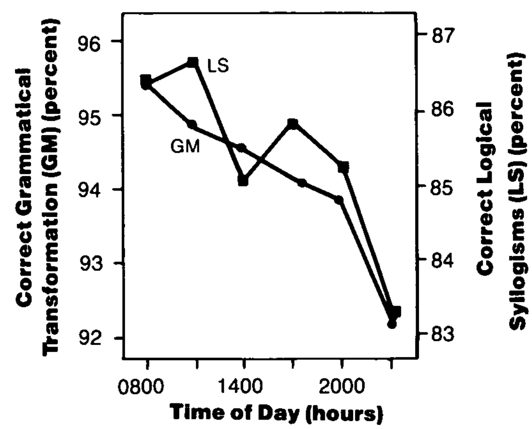

Figure 2. Percentage of items correct on the grammatical transformation (GM) and logical syllogism (LS) tasks as a function of time of day. (From Ref. 3)

Key Terms

Circadian rhythms; decision making; diurnal variation; memory; time of day

General Description

When subjects perform two self-paced tests of logical reasoning, involving both short-term memory and immediate processing (or speeded decision making), speed increases in the morning, peaks in the early afternoon, then decreases while accuracy declines throughout the day.

Methods

Test Conditions

- Grammatical transformation task (GMT): 32 sentences (e.g., B is not preceded by A) each describing a relationship between the letter "A" and the letter "B" followed by either the letter pair "AB" or the letter pair "BA"; six versions of task, each with 32 items repeated twice; versions differed in order of presentation of items
- Logical syllogism task (LST): two statements (e.g., No birds are insects. All swallows are birds.) followed by four possible conclusions (e.g., Some birds are not swallows; all birds are swallows; no swallows are insects; no insects are birds.), only one of which followed logically (the third sentence); six versions, each consisted of a different set of 24 items
- Six groups of subjects based on time of first session, 0800, 1100, 1400, 1700, 2000, or 2300 hr; half of each group given 3 min of GMT, followed by 3 min rest and 3 min of LST; reverse order for other half; each subject tested at all six times
- 6 subjects who began at 0800 hr completed test in a single day (15 hr); all other subjects completed test over 2 days (21 hr) with a normal period of sleep between days
- At beginning of first session, subjects were given completed examples of both tasks and full written instructions for the tasks; no practice sessions

Experimental Procedure

- Independent variable: time of day
- Dependent variables: number of grammatical transformations (GM) performed, number of logical syllogisms (LS) performed, GM accuracy (percentage of GM correct), LS accuracy (percentage of LS correct)
- Subject's task: GMT: compare sentence and letter pair to decide truth or falsity of statement; LST: choose one of four conclusions which logically follows each premise
- Subjects: 19 female and 17 male undergraduates, 18-24 yr

Experimental Results

- Time of day significantly affects the number of items performed in both tasks (GMT, $p < 0.01$; LST, $p < 0.05$), with speed improving from 0800 to 1400 hr (Fig. 1).
- Time of day does not directly affect the percentage of items correct (see Fig. 2), but when the linear components are extracted, they account for a large proportion of the variance associated with time of day (GMT: 88%, LST: 67%), although the linear component achieves significance for only GMT ($p < 0.01$).

Variability

Significance was determined by analysis of variance.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Repeatability/Comparison with Other Studies

Effect of time of day on short-term memory is characterized by an improvement between early and mid morning, followed by a decline over rest of day (Refs. 1, 2). In self-paced tasks, speed is more sensitive to time of day effects than accuracy (Ref. 2).

Constraints

- Tasks with little or no memory load, but that require immediate processing, show continuous rise in performance throughout the day (Ref. 2).

Key References

1. Baddeley, A. D., Hatter, J. E., Scott, D., & Snashall, A. (1970). Memory and time of day. *Quarterly Journal of Experimental Psychology*, *22*, 605-609.

2. Blake, M. J. F. (1967). Time of day effects on performance in a range of tasks. *Psychonomic Science*, *9*, 349-350.

*3. Folkard, S. (1975). Diurnal variation in logical reasoning. *British Journal of Psychology*, *66*, 1-8.

Cross References

10.701 Characteristics of biological rhythms;

10.702 Circadian variation in body temperature;

10.704 Time of day: effect on memory;

10.706 Time of day: effect on speeded decision making;

10.707 Circadian variation in work efficiency;

10.711 Circadian variation in vigilance performance and body temperature for individuals with different work shift preferences

10.706 Time of Day: Effect on Speeded Decision Making

Key Terms

Circadian rhythm; decision making; diurnal variation; memory; time of day

General Description

Tasks with low memory loads, but requiring immediate processing (i.e., speeded decision-making), show the effect of time of day on performance. Performance tends to improve later in the day, but with a clear post-lunch decline. On self-paced tasks, speed, not accuracy, is sensitive to time of day effects. Table 1 describes each task and lists the significance levels of the time-of-day effects. Results are shown in Fig. 1.

Methods

Test Conditions

- After preliminary training each subject tested once in isolation without knowledge of results
- Each subject tested at 0800, 1030, 1300, 1530 and 2100 hr
- Subject tasks described in Table 1
- One session per day for 5 consecutive days, but occasionally tests at 0800 hr and at 2100 hr were on same day

Experimental Procedure

- Latin square design with repeated measures
- Independent variables: time of day (0800, 1030, 1300, 1530, 2100 hr)
- Dependent variables: specific to each task (listed in Table 1)
- Subjects were Naval personnel ages 17-33 yr, some practice

Constraints

- Other factors, such as introversion/extroversion, morning/evening work preference, and age, influence time-of-day effects on performance.
- Because of the impact of individual differences on time-of-day effects, it is important to know whether tasks are performed by the same or different sets of subjects.

Table 1. Description of tasks.

Task	Description	Task Duration	Number of Subjects	Dependent Variables	Significance Level of Effect of Time of Day
Serial reaction	Five lamps in pentagon; five metal disc response circuits; order of light presentation, random; taping any disc altered display	30 min	30	Correct responses	$p<.05$
				Incorrect responses	NS
				Gaps (responses > 1.5 sec)	$p<.05$
Card sorting	Eight 64-card packs comprising playing card packs with 9's, 10's, and face cards removed; cards were sorted into two (red and black) and eight categories (i.e., by number)	12-15 min	30	Sorting time for two categories	$p<.001$
				Sorting time for eight categories	$p<.001$
Calculations	Columns of five, two-digit numbers summed at subject's own pace	60 min	25	Number of calculations attempted	$p<.001$
				Percentage error	NS
Vigilance	Nonsignal target: 500-Hz, 600-msec tone every 3 sec; signal target: twenty-four 500-Hz, 670-msec tones; signal target schedule: random	53 min	25	Correct detections	$p<.025$
				Incorrect detections	NS
Letter cancellation	Pages of English prose were checked for letter "e"; signal target "e" cancelled	30 min	25	Number of letter "e" processed.	$p<.001$
				Percentage of omission errors	NS

NS = Variation with time of day is nonsignificant

Key References

*1. Blake, M. J. F. (1967). Time of day effects on performance in a range of tasks. *Psychonomic Science*, *9*, 349-350.

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Cross References

10.701 Characteristics of biological rhythms;

10.702 Circadian variation in body temperature;

10.704 Time of day: effect on memory;

10.705 Time of day: effect on short-term memory and speeded decision making;

10.707 Circadian variation in work efficiency;

10.711 Circadian variation in vigilance performance and body temperature for individuals with different work shift preferences;

Handbook of Perception and Human Performance, Ch. 44, Sect. 4.2

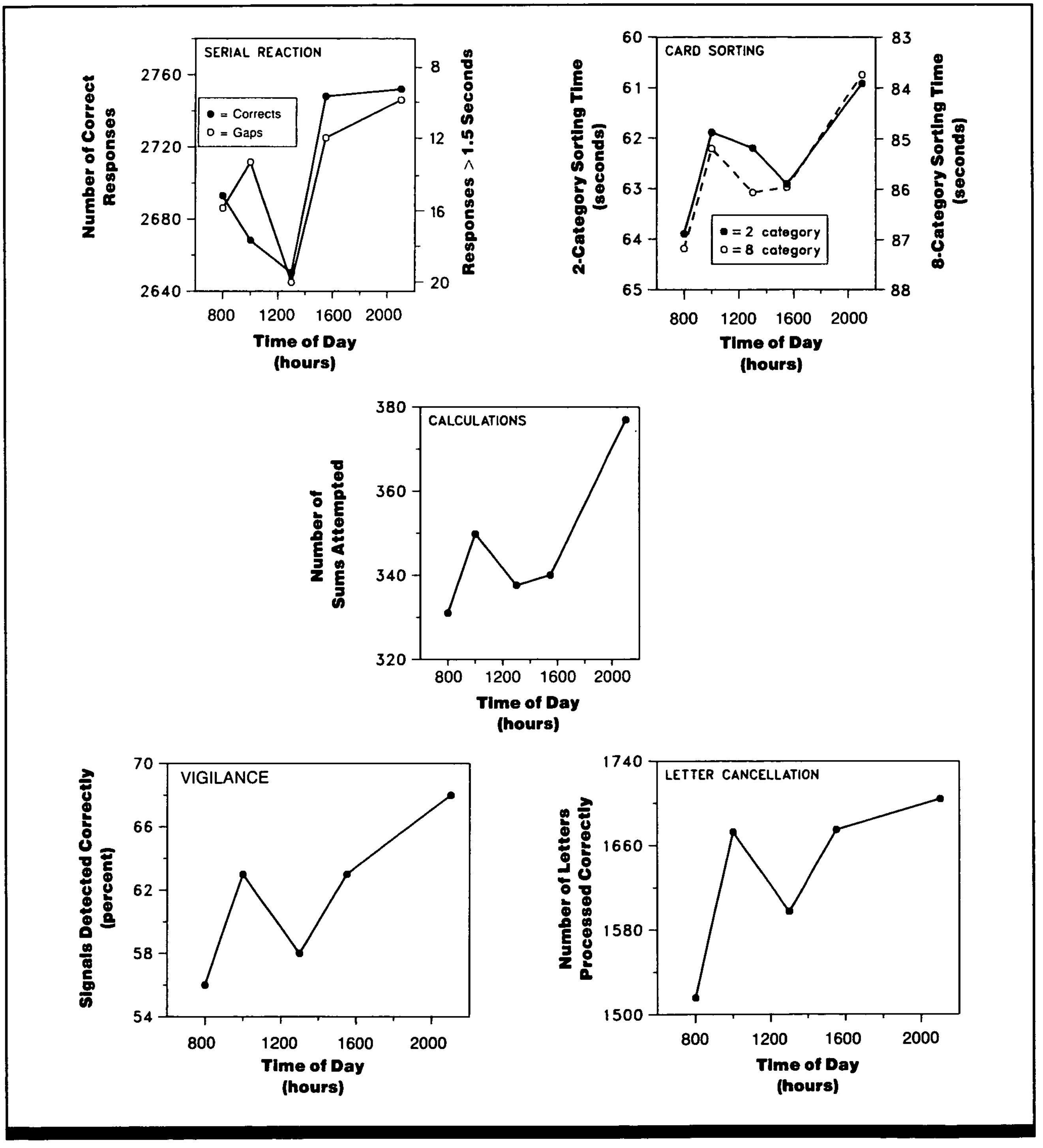

Figure 1. Effect of time of day on performance of 5 different tasks requiring immediate processing. (From Ref. 2, based on data of Ref. 1)

10.707 Circadian Variation in Work Efficiency

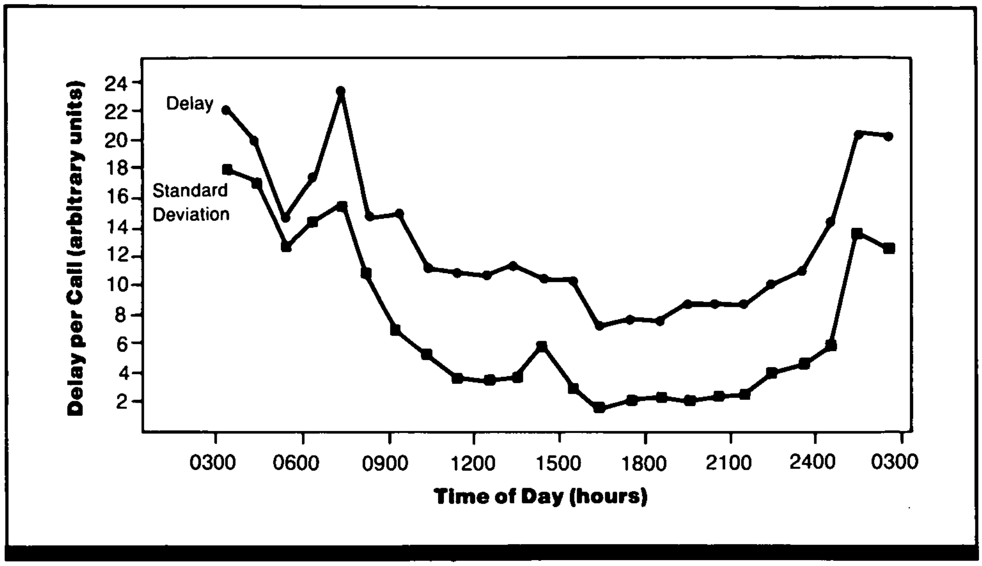

Figure 1. Delay per call as a function of time of day for teleprinter switchboard operators. (From Ref. 2)

Key Terms

Circadian rhythm; diurnal variation; fatigue; workload

General Description

Field studies show convincing evidence for a circadian (~24 hr) rhythm in work efficiency. Teleprinter switchboard operators take longer to respond to subscribers' requests for a connection between 2400 and 0800 hr than on any other shift (top curve, Fig. 1), despite a decrease in task demand (number of requests per operator) for most hours of the night. On all three shifts, 0800-1600, 1600-2300, and 2300-0800, fatigue occurs, but does not dominate the rhythm. Increased variability of time to answer a call seems to be a manifestation of fatigue (bottom curve, Fig. 1). Circadian variations in performance are also seen with other tasks (Figs. 2 and 3).

Applications

Implications for work/rest scheduling and performance expectations in shift work.

Methods

Test Conditions

- Subject seated before teleprinter switchboard
- Flashing call light signals that subscriber is asking for connection
- Delay in answering light determined by measuring current consumption, with a recording ammeter, of all calling lights on switchboard; number of calls also measured continuously by counting system
- Duration of field study: 3 months

Experimental Procedure

- Independent variable: time of day
- Dependent variables: delay in answering flashing call lights, number of calls averaged per hour (load)
- Subject's task: operate teleprinter switchboard by providing connection in response to flashing light
- Experienced teleprinter operators in the Women's Auxiliary Air Force served as subjects

Experimental Results

- Average number of calls per subject per hr rises from 25 at 0800-0900 to 81 at 1200-1300, fluctuates between 69 and 93 until 1900-2000, and then declines sharply to 45 between 2200 and 2300. A secondary rise with a peak of 74 occurs at 0100-0200, gradually falling off after that to 30 at 0500-0700.
- 0800-1600 shift: performance improves (shorter delay per call) until midday after which there is little change until subjects are replaced by next shift at 1600 hr (Fig. 1).
- 1600-2300 shift: shift begins with shorter delays than shift being replaced, but the delay in answering increases steadily throughout the shift.
- 2300-0800 shift: performance deteriorates throughout the shift except for some improvement from 0500-0700.
- Performance throughout the 24-hr period shows a well-marked rhythm, being best in the afternoon, but deteriorating throughout the night and improving again during the morning.
- Within the same hours during the day, pressure of work does not affect performance (same mean delay per call despite varied call load), but at night, when calls are few, increased load tends to improve performance.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Somewhat similar patterns of circadian variation in work efficiency are reported for errors in gas-meter reading (Ref. 1 and Fig. 2) and frequency of falling asleep while driving (Ref. 4 and Fig. 3). Dissimilarities may be related to differences in shift change times. Reversal just after noon corresponds to "postprandial dip" seen in temperature and performance measures.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Because these are all field studies, there is no control over the amount of sleep obtained by workers of each shift. Night workers often complain of difficulty sleeping during the day (Ref. 3), so that fatigue and time of day (or amount of sleep) effects may interact.

• Workload variability at night may be a bigger factor than any circadian variation.

Key References

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Cross References

10.701 Characteristics of biological rhythms;

10.702 Circadian variation in body temperature;

10.704 Time of day: effect on memory;

10.705 Time of day: effect on short-term memory and speeded decision making;

10.706 Time of day: effect on speeded decision making;

10.710 Adaptation of circadian rhythms to altered schedules;

10.712 Schedule shift: effect on performance;

10.809 Partial deprivation of sleep: effect on performance;

Handbook of perception and human performance, Ch. 44, Sect. 4.2

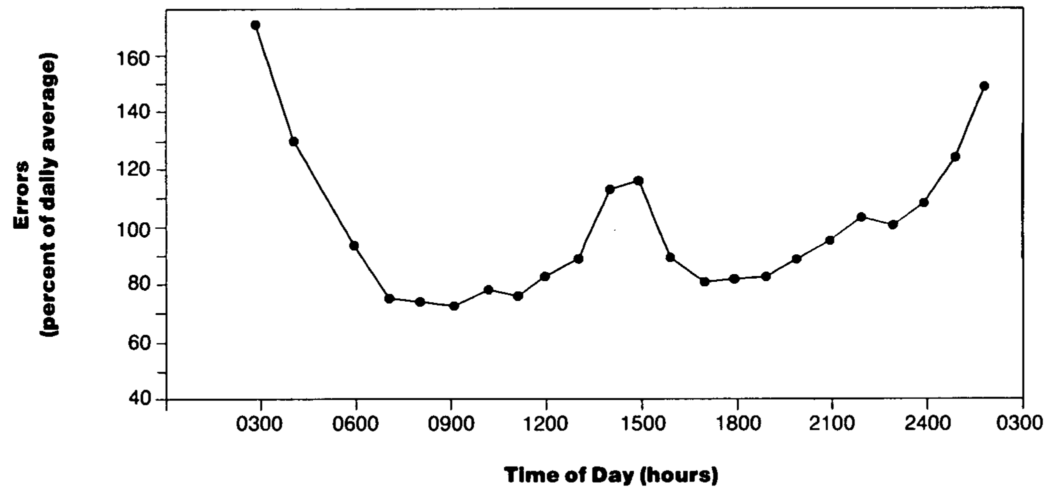

Figure 2. Errors in reading gas meters as a function of time of day. Data are means of 62,000 observations. (From Ref. 3)

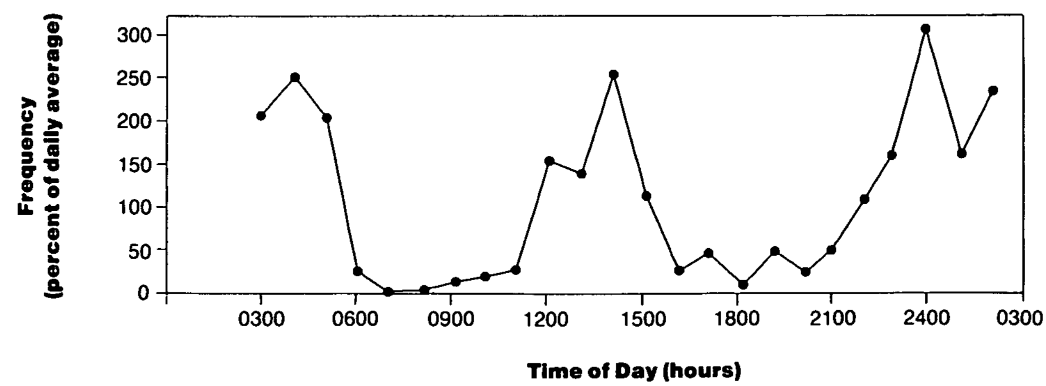

Figure 3. Frequency of falling asleep while driving as a function of time of day. Data are means of 500 observations. (From Ref. 3)

10.708 Incentive and Introverted/Extroverted Personality: Effects on the Diurnal Rhythm of Performance

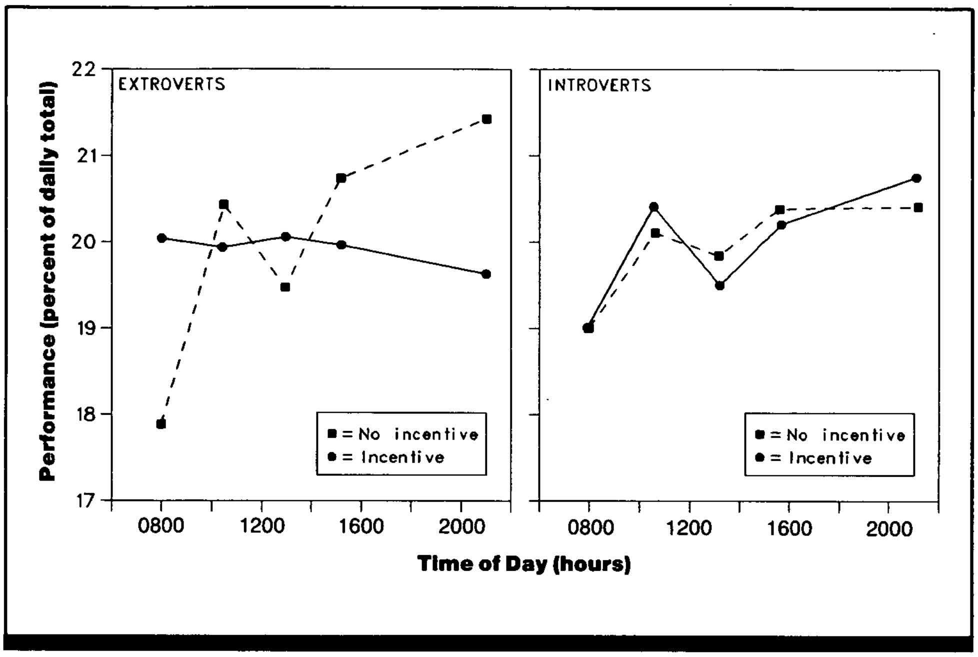

Figure 1. Performance as a function of time of day and incentive for extroverts and introverts. (From Ref. 4)

Key Terms

Body temperature; circadian rhythm; diurnal variation; incentive; introversion; motivation; operator selection; personality

General Description

Performance of extroverts and introverts shows time of day effects on a self-paced cancellation task (cross out all letter "e's" in text). Introverts are faster than extroverts in the early morning, whereas the extroverts' speed is greater late in the day. When informed continuously about their performance (knowledge of results), extroverts' morning performance improves, but evening performance declines, abolishing a diurnal performance rhythm (left panel, Fig. 1). The incentive of knowledge of results has a minimal effect on the speed of introverts' performance (right panel, Fig. 1).

Methods

Test Conditions

- Subjects selected on the basis of scores for introversion (>4) or extroversion (<4) on the Heron scale
- Subject seated alone in room
- In incentive condition, knowledge of results provided (method not described)
- Sheets of English prose; signal target: letter "e"; administered at 0800, 1030, 1300, 1520, or 2100 hr
- One 15-min test session per day for 5 consecutive days; occasionally tests at 0800 and 2100 hr were on same day

Experimental Procedure

- Independent variables: introversion or extroversion of subject; incentive, defined as knowledge of results (provided or not provided); time of day
- Dependent variable: speed, defined as number of lines of prose in which "e's" were cancelled (expressed as percentage of total output for the day)
- Subject's task: cancel all letter "e's"
- Subjects: naval personnel, age 17-33 yrs (number not given)

Experimental Results

- At the earliest time of testing (0800 hr), introverts complete a higher percentage of their day's output than do extroverts.
- By the latest time of testing (2100 hr), extroverts produce a higher percentage of their day's output than do introverts.
- Knowledge of results (incentive) has a minimal effect on the diurnal performance rhythm of introverts, but it improves the morning performance of extroverts and appears to impair their evening performance.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Introverts prefer morning work, and extroverts prefer evening work; those who prefer morning work have a peak effi-

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

ciency at inspection performance early in the day, while those who prefer evening work improve throughout the day (CRef. 10.711). Knowledge of results has a greater effect on the performance of extroverts than introverts (Ref. 5), although it usually improves performance. In a complicated study of the effects of caffeine (thought to be an arouser-like incentive), the stimulant interacted not only with introversion/extroversion and time of day, but also with practice (that is, day of testing) (Ref. 6).

Constraints

- Reference 4 does not make clear whether the same subjects served in both knowledge of results conditions.
- Since the testing was limited to 0800-2100 hr, the diurnal rhythm of extroverts seems more pronounced, but body temperature rhythms of introverts are phase-advanced over the body temperature rhythms of extroverts (Ref. 1), so that if earlier and/or later hours of testing had been included, the performance patterns might have shown similar amplitudes.
- Post-lunch decrement in performance is thought to be unrelated to introversion/extroversion (Ref. 4).
- Reporting results as percent of daily output allows only relative conclusions. It is possible that actual speed of extroverts' evening work may have been improved by incentive.

Key References

1. Blake, M. J. F. (1967). Relationship between circadian rhythm of body temperature and introversion-extroversion. *Nature, 215*, 896-897.

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Cross References

7.801 Effect of incentive on performance;

7.803 Effect of anxiety on performance;

7.804 Effects of stress on performance for introverts and extroverts;

10.101 Theories of arousal and stress;

10.104 Arousal level: effect on performance;

10.707 Circadian variation in work efficiency;

10.711 Circadian variation in vigilance performance and body temperature for individuals with different work shift preferences;

Handbook of perception and human performance, Ch. 44, Sect. 7.2

10.709 Ultradian Rhythms

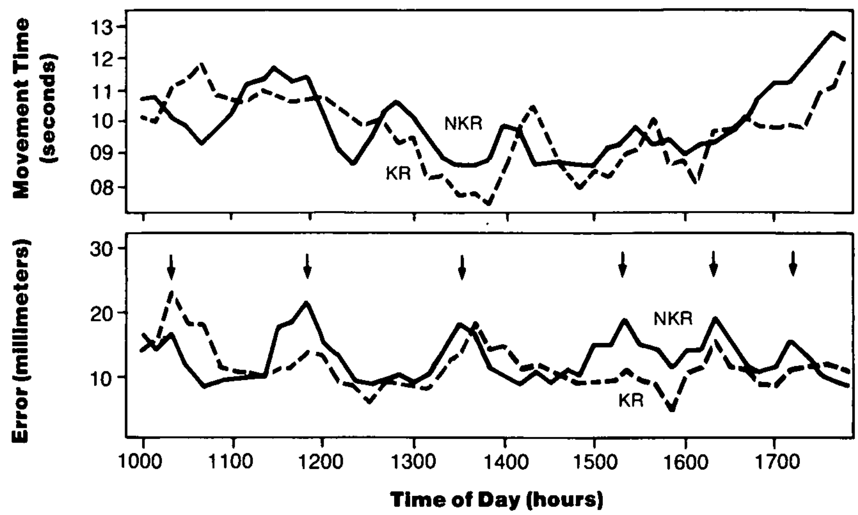

Figure 1. Ultradian rhythms in error in a linear positioning task for which subjects knew (KR) or did not know (NKR) results of performance. Arrows indicate peaks in errors. Upper panel shows variations in movement time superimposed on slow trend, probably reflecting circadian trend. (From Ref. 7, based on Ref. 9)

Key Terms

Biological rhythms; circadian rhythm; sleep; ultradian rhythm; vigilance

General Description

Performance on some tasks (and some measures of physiological processes) varies in cycles with periods of ~90 min, exhibiting a periodicity similar to that of sleep stages in a night's sleep (CRef. 10.703). Unlike light/dark and other external time cues related to circadian rhythms, no time cues are known to have a natural periodicity within the ultradian (less than a day) range of ~90 min. Nevertheless, cycles with 90 ± 10 min periodicity have been demonstrated repeatedly.

The sparse research on the detection of ultradian rhythms during waking suggests that a multi-oscillatory system controls ultradian variations. The table lists the tasks and physiological processes that have been studied and indicates those that show ultradian periodicity.

Constraints

- As with other biological rhythms, there is great individual variation in periodicity, phase, and amplitude of ultradian rhythms.
- Many studies in which rhythmicity is observed do not report the statistical significance of the data, nor the relative contribution of the ultradian rhythmicity to the total variance.
- Because so few studies measure multiple tasks or processes which might show ultradian cycles, correlations between them cannot be determined.

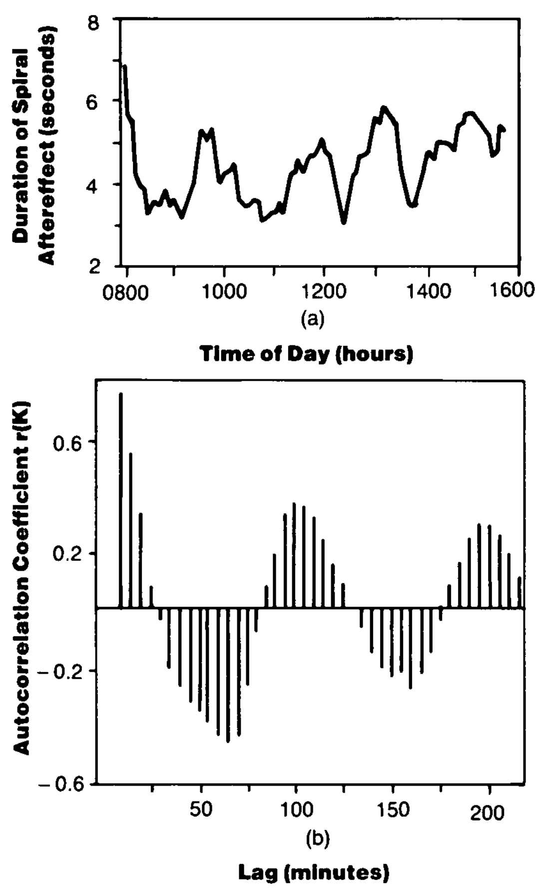

Figure 2. Ultradian rhythms in (a) the duration of the spiral aftereffect and (b) corresponding autocorrelation. One lag unit equals 5 min. (From Ref. 7, based on Ref. 9)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Ultradian rhythms in performance tasks and physiological processes.

Performance	Description	Effect	Source
Vigilance	6-hr continuous task	Equivocal 100-min cycles	Ref. 2
	Prolonged complex task (with heart rate)	Complex demodulation reveals 90-min cycle in performance, weakly and inconsistently related to changes in heart rate	Ref. 11
Linear positioning	Move a lever 20 cm along a metal rod, using only auditory cues (tone's frequency varied with displacement) and proprioceptive stimuli (weight attached to spring of lever) with (KR) or without (NKR) knowledge of results; also measured urine flow volume; from 0800-1800 hr	Performance results shown in Fig. 1; positioning errors show 100-min periodicity and large amplitude rhythm, accounting for 20% of variance (30% in some subjects) Rapid 20- to 40-min fluctuations in accuracy in KR condition; 100 min periodicity in NKR condition No significant periodicity in speed of performance in either condition Urine volume shows ultradian rhythm not consistently related to performance	Ref. 3
Adaptive serial reaction time	Random number displayed on CRT; correct response shortens display time on next trial by 20 msec; error or long RT lengthens next trial by 20 msec; from 0800-2000 hr and 2000-0800 hr	Spectral analysis of mean and modal display time reveals no ultradian rhythm in either day or night session	Ref. 7
Perceptual illusions	Spiral aftereffect illusion (apparent motion experienced after fixation of a rotating spiral) tested at 5-min intervals in an 8-hr day session and an 8-hr night session	Fluctuations in the duration of the illusion describe a clear 90-min rhythm (shown with autocorrelation functions in Fig. 2)	Ref. 9
	Phi phenomenon, during which a spot of light flashes successively at two different points but appears as a spot continuously moving across the field	Synchronizes with spiral aftereffect	Ref. 5
Pupillary size	Pupillary size and an index of pupillary stability in constant illumination conditions, monitored every 15 min for 10 hr	70- to 90-min rhythm in the two means accounts for 17-20% of the variance	Ref. 6
Sleep and daydreaming	Daydreaming, EEG, and waking rapid eye movement (REM)	Daydreams occur at 90 min intervals, correlating with alpha EEG and diminution of REM	Ref. 4
	Nine subjects instructed to close eyes and fall asleep during 5-min period of darkness at 15-min intervals for 12 hr	Significant untradian 90-min periodic fluctuations in Stage 1 sleep measured by EEG Ability to fall asleep also modulated by circadian rhythm	Ref. 10
Ingestion (eating)	Allowed free access to food	80 to 100-min cycle in eating behavior	Ref. 1
Digestion	Gastric contractions while awake and asleep	100-min period	Ref. 7
Excretion	Volume of urine flow in waking subjects	90-min cyclicity	Ref. 8
Endocrine (hormone secretion)	Parathyroid, antidiuretic, and luteinizing hormones	80 to 100-min period	Ref. 7

Key References

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Cross References

10.701 Characteristics of biological rhythms;

10.703 Cyclical patterns of sleep;

10.707 Circadian variation in work efficiency

Notes

10.710 Adaptation of Circadian Rhythms to Altered Schedules

Key Terms

Body temperature; circadian rhythm; diurnal variation; fatigue; stress

General Description

Performance, as well as fatigue, body temperature (BT), endocrine secretion and cardiovascular, respiratory, metabolic, and gastrointestinal functions, show circadian rhythms. Flight across time zones or shift work alter the schedule of sleep/wake or work/rest cycles and affect circadian rhythms.

The extent to which a circadian rhythm is endogenous (determined internally) or exogenous (determined externally) strongly influences the rate, form, and degree of adaptation to schedule shifts. A completely exogenous rhythm adapts completely and immediately (see C in Fig. 1). Since most processes have an endogenous component, adaptation is typically gradual and incomplete, possibly retaining a peak at the old phase or flattening in the overall range of oscillation. An example is the BT rhythm shown for the 4 days after a 6-hr phase delay (B in Fig. 1) (CRefs. 10.701, 10.702).

With rapid time zone change, all the social and physical time cues reinforce the new schedule, but for shift work, the environment is antagonistic to the schedule. Travel from east to west (and a change from day- to night-shift work) causes a phase delay, while travel from west to east (and a change from regular-day to early-morning shift work) causes a phase advance in the sleep/wake cycle. In general, circadian rhythms seem to adapt more quickly, completely, and regularly to phase delays than to phase advances, probably because many processes have a free-running rhythm slightly longer than a 24-hr day (CRef. 10.714).

The table describes the ways in which laboratory isolation differs from field studies of time-zone and shift-work change, the factors affecting adaptation of the rhythm to new schedules, and the time span and degree of adaptation of BT to new schedules.

Table 1. Factors affecting adaptation during laboratory studies.

Cause of Altered Schedule	Laboratory Isolation Effects	Effect on Adaptation	Adaptation Time/Degree	Source
Time-zone (all social and physical time cues reinforce new schedule)	Tension, stress, fear, fatigue (loss of sleep) associated with actual flights are avoided	Faster for stronger time cues after shift	BT adaptation complete after 8 days	Ref. 2 CRef. 10.713
		Faster for travel east to west than vice versa		
	Less reinforcement by social and physical time cues	Faster for flight toward home than away from home		
		Faster for smaller shifts, (see phase response curve), but initial rate of adaptation greater for larger shift		
Shift-work (all social and physical time cues contradict new schedule)	Prevents return to day schedule during rest days	Faster for shift to night work than shift to early morning work		Ref. 1
	More reinforcement by social and physical time cues	Steady shift alters rhythms, while rapidly rotating shift does little to change them, but worker is then working at lowest point of BT rhythm and highest point of fatigue cycle	BT adaptation almost complete by Day 21 (with no break in night shift work) and some flattening of amplitude BT shows greatest adaptation on Day 6 or 7 (lost in 2-day weekend at normal schedule)	
		Working a 1-1-1 shift system (first day, morning shift; second day, afternoon shift; third day, night shift; fourth day off) or a 2-2-2 shift system (2 days at each shift) leads to minimal BT alteration, but work not at peak efficiency		CRef. 10.712

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Cause of Altered Schedule	Laboratory Isolation Effects	Effect on Adaptation	Adaptation Time/Degree	Source
Shift-work (cont.)		Change from sleep-work-leisure schedule to sleep-leisure-work contributes to varied form of adaptation		CRef. 10.712
		Faster for positive worker attitude and willingness to change day-off schedule to support adaptation		CRef. 7.417
Time zone and shift-work	Better control over schedule	Faster for processes that are internally driven (endogenous) than for externally driven (exogenous) processes (i.e., related to sleep/work cycle)		Ref. 2 CRef. 10.807
		Faster for phase delay than phase advance		Ref. 2
		Faster if subject remained on previous schedule (before alteration) only briefly		
		Task type (faster for tasks involving working memory adaptation than those requiring speeded processing only)		CRefs. 10.201, 10.704, 10.705 10.706
		Individual differences are large: slower for older subjects, introverted subjects, and subjects whose rhythms show larger amplitudes		Ref. 2 CRefs. 10.708, 10.711

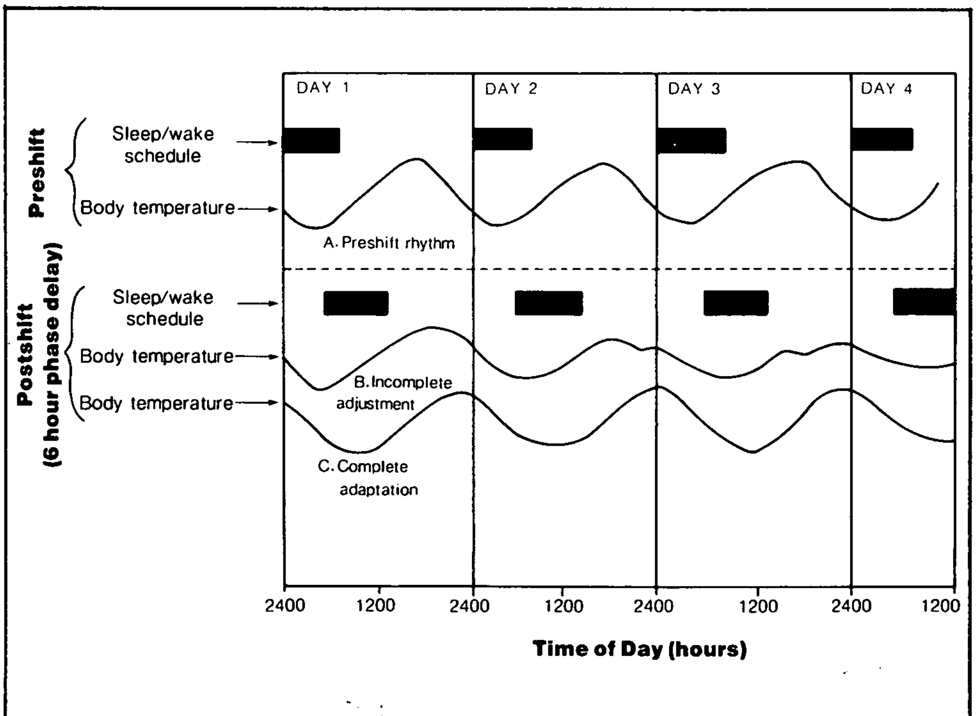

Figure 1. Adaptation to shifts of phase. Figure shows a hypothetical body temperature (BT) rhythm for 4 days preceding and following a 6-hour phase delay in the sleep/wake schedule (horizontal bars). The preshift rhythm (A) has a peak at about 1800 hours. After the change to the later sleep time, the BT rhythm has to adapt to the altered schedule of work and sleep. Complete adaptation is shown in C, where the rhythm immediately adopts the new phase by a 6-hour advance. More typical is rhythm shown in B, where the adaptation is gradual and incomplete. (From *Handbook of perception and human performance*)

Constraints

• With shift work, fatigue caused by difficulty in sleeping during the noise of the day confuses measures of circadian rhythms (CRef. 10.808).

• Even in a quiet environment, for most individuals, sleep during the day time is not a normal event and therefore requires a period of adaptation before sleep can be restful during daylight.

Key References

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*2. Minors, D. S., & Waterhouse, J. M. (1981). *Circadian rhythms and the human*. London: Wright PSG.

Cross References

7.417 Effect of boredom on detection efficiency;

10.201 Types of tasks used in measuring the effects of stress, fatigue and environmental factors on performance;

10.701 Characteristics of biological rhythms;

10.702 Circadian variation in body temperature;

10.703 Cyclical patterns of sleep;

10.704 Time of day: effect on memory;

10.705 Time of day: effect on short-term memory and speeded decision making;

10.706 Time of day: effect on speeded decision making;

10.707 Circadian variation in work efficiency;

10.708 Incentive and introverted/extroverted personality: effects on the diurnal rhythm of performance;

10.711 Circadian variation in vigilance performance and body temperature for individuals with different work shift preferences;

10.712 Schedule shift: effect on performance;

10.713 Rapid time-zone shifts: effect on performance and body temperature;

10.714 Sleep/wake and body temperature cycles during isolation from external time references;

10.807 Sleep deprivation: use of physiological indicators to predict performance decrement;

10.808 Sleep deprivation: effect on circadian rhythm;

Handbook of perception and human performance, Ch. 44, Sect. 4.2

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

10.711 Circadian Variation in Vigilance Performance and Body Temperature for Individuals with Different Work Shift Preferences

Key Terms

Body temperature; circadian rhythm; diurnal variation; vigilance

General Description

Subjects preferring morning (M) or evening (E) work differ slightly, but consistently, in the phase of the body temperature (BT) rhythm (about 1-2 hr); however, there is a marked difference in the performance rhythms of the two groups. In a vigilance task, E workers perform best in the evening (2000 hr), M workers in the morning (1200 hr). The E group's performance improves throughout the day, whereas the M types show a sharp post-lunch decrement followed by continued deterioration in performance.

Methods

Test Conditions

- Subjects completed and grouped by results of English language Morningness-Eveningness self-assessment questionnaire (Ref. 5.)
- Playing cards presented face up, spaced 3 cm apart in single line on conveyor belt which traveled from left to right at 9.2 m/min
- Subjects seated at conveyor belt, with 115 cards presented per min, for simulated production line inspection task
- Signal targets: cards with one of four equiprobable (probability 0.08) simple faults (not described)
- 15 to 20-min sessions (one each hour) from 0800 hr (Session 1) to 2200 hr (Session 15); first 5 min of each session considered warm-up (data not analyzed); each subject participated in an average of three sessions per day, randomized over five consecutive days
- Oral temperature taken at each session

Experimental Procedure

- Independent variables: work preference (M or E type), time of day
- Dependent variables: oral temperature; correct detection of signal targets (hits) and incorrect detection of nonsignal targets (false alarms), both corrected for practice effects
- Subject's task: detect and remove or identify signal targets (defective cards)
- 20 subjects, 5 men and 5 women, 18-30 yr, in each of two groups; some practice

Experimental Results

- Both M and E groups perform consistently well throughout the day on the false alarm condition, rejecting only 0.5-1% of the perfect cards.
- Correct detection of signal targets differs significantly between the two groups over the day ($p < 0.001$) (Fig. 1).
- Peak performance (correct detection level) occurs ~1200 hr for M types and at ~2000 hrs for E types.
- BT peaks at about the same time for both groups (Fig. 1).
- Correct detection (accuracy) level and BT correlate positively for E types ($r = 0.89, p < 0.01$), but negatively for M types ($r = -0.81, p < 0.01$).

Variability

Significance was determined by correlation and analysis of variance. Two subjects did not fit the general pattern of results: one M subject showed little difference in performance early and later in the day; one E subject performed far worse in the morning and better in the evening than other E types.

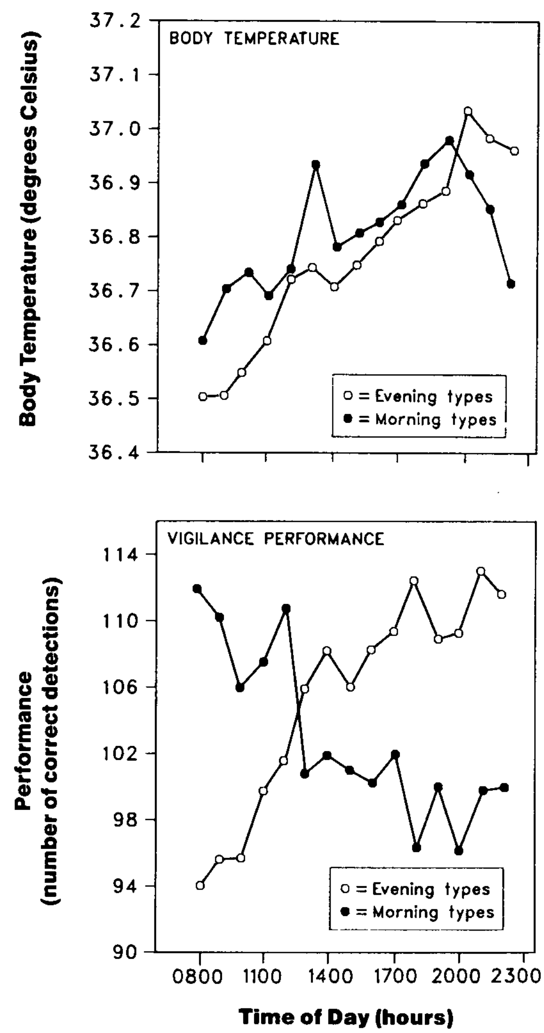

Figure 1. Body temperature and vigilance performance as a function of time of day for subjects preferring morning or evening work. (From Ref. 2, based on data from Ref. 3)

Repeatability/Comparison with Other Studies

Individual differences in the circadian rhythm of oral temperature are more marked when subjects are classified on the morning/evening preference continuum than on an introversion/extroversion scale (Ref. 4); however, introversion-morning preference/extroversion-evening preference correlate highly (Ref. 1). Significant M-E type differences were reported for reaction times at three times on a single day (Ref. 6).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Type of task, degree of memory required, and task pacing also influence circadian rhythm of performance.
- Systematic practice and fatigue effects have been shown; had each subject undergone all sessions in one day, results may have been different.

Key References

1. Blake, M. J. F., & Corcoran, D. W. J. (1972). Introversion-extroversion and circadian rhythms. In W.P. Colquhoun (Ed.), *Aspects of human efficiency: Diurnal rhythm and loss of sleep* (pp. 261-272). London: English Universities Press.

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Cross References

10.101 Theories of arousal and stress;

10.103 Classification of factors influencing the stress state;

10.104 Arousal level: effect on performance;

10.701 Characteristics of biological rhythms;

10.702 Circadian variation in body temperature;

10.704 Time of day: effect on memory;

10.705 Time of day: effect on short-term memory and speeded decision making;

10.706 Time of day: effect on speeded decision making;

10.707 Circadian variation in work efficiency;

10.708 Incentive and introverted/extroverted personality: effects on the diurnal rhythm of performance;

Handbook of perception and human performance, Ch. 44, Sect. 4.2

10.712 Schedule Shift: Effect on Performance

Table 1. Performance on four tasks as a function of time since arising for normal and shifted schedules.

Task	Dependent Variable	Effect
Manual dexterity:		
Exchanging nuts and bolts attached to one of two brass plates	Time required to complete exchange	Fig. 2
Visual search:		
Search lines of Os for slightly tilted Os	Number of lines checked in 90 sec	Fig. 3
Arithmetic:		
Add columns of 2-digit numbers	Number of columns added in 5 min	Fig. 4
Verbal reasoning:		
Select conclusion which logically follows two premises of syllogism	Number of syllogisms completed in 3 min	Fig. 5

Key Terms

Body temperature; circadian rhythm; cognitive tasks; diurnal variation; manual dexterity; time of day; verbal reasoning; visual search

General Description

When the sleep/work schedule of a socially isolated community was shifted by 8 hr for 10 days, circadian rhythm of body temperature did not completely adapt during the shift period (Fig. 1), nor did performance on manual dexterity and visual search tasks. Complete adaptation occurred for performance on arithmetic and verbal reasoning tasks, which involve more memory load than the other tasks.

The table and Figures 2-5 compare performance on four tasks for the 2 pre-shift days and the 9th and 10th days of the shift period, measured at 4-hr intervals after arising. For all tasks, the functions represent percentage deviation from the overall mean for the day to allow comparisons between tasks.

Methods

- General social isolation (survey camp in Antarctic), but half the staff members did not vary their schedules
- Under normal conditions, subjects slept from 2400 to 0800 hr; under shifted schedule, subjects slept from 0800 to 1600 hr; no light-dark or other environmental changes made
- For 2 days before shift and for the last 2 days of the shifted schedule (Days 9 and 10), subjects took four tests of performance efficiency and measured their urine-flow temperature at 4-hr intervals throughout waking day
- 6 subjects, members of a British Antarctic Survey Camp

Constraints

- Schedule is not comparable to that for shift workers because work followed sleep and leisure followed work, whereas most shift workers (who are not socially isolated) have their leisure time after sleep and before work.
- Apparent lack of adaptation at 12 hr (0400 hr real time) after rising (Fig. 2) may be attributable to core temperature being at its lowest at this time under a normal schedule.

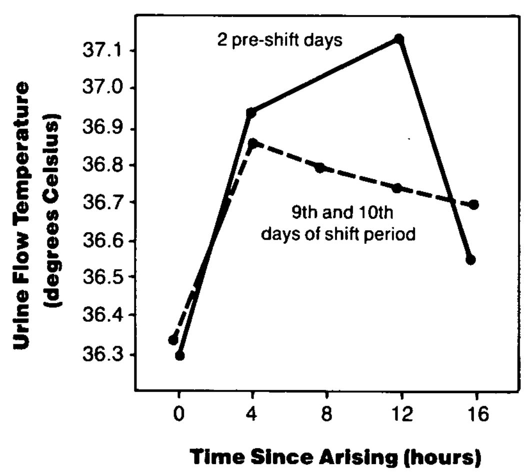

Figure 1. Urine flow temperature as a function of time since arising. (From Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Hughes, D. G., & Folkard, S. (1976). Adaptation to an 8-hr shift in living routine by members of a socially isolated community. *Nature*, *264*, 432-434.

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Cross References

10.701 Characteristics of biological rhythms;

10.702 Circadian variation in body temperature;

10.704 Time of day: effect on memory;

10.705 Time of day: effect on short-term memory and speeded decision making;

10.706 Time of day: effect on speeded decision making;

10.710 Adaptation of circadian rhythms to altered schedules;

10.713 Rapid time zone shifts: effect on performance and body temperature;

10.808 Sleep deprivation: effect on circadian rhythm

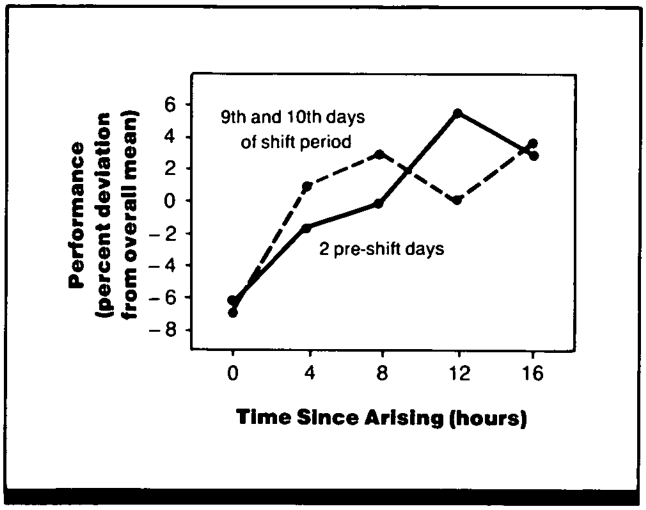

Figure 2. Performance on manual dexterity task as a function of time since arising. (From Ref. 1)

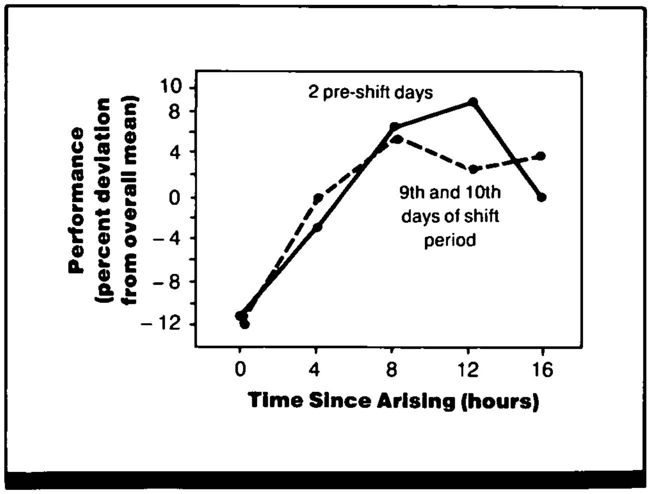

Figure 3. Performance on visual search task as a function of time since arising. (From Ref. 1)

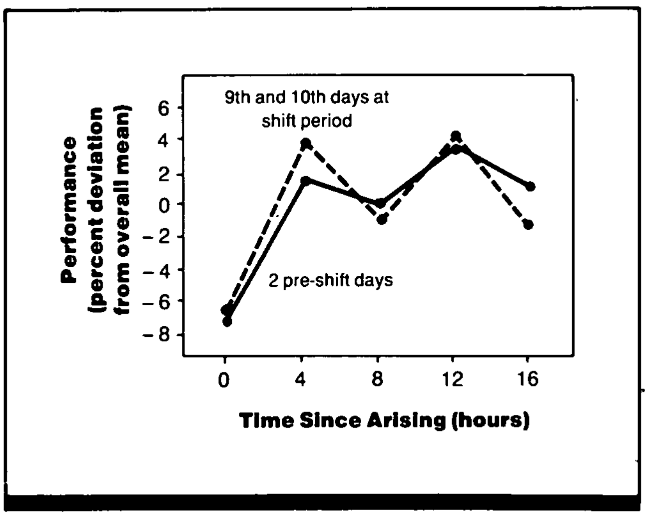

Figure 4. Performance on an arithmetic task as a function of time since arising. (From Ref. 1)

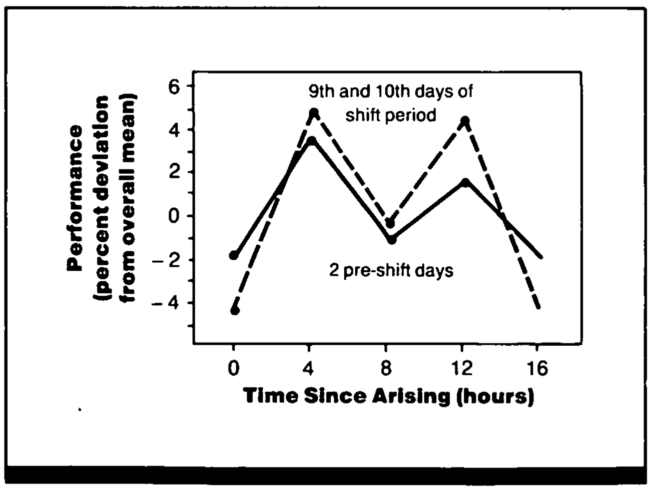

Figure 5. Performance on a verbal reasoning task as a function of time since arising. (From Ref. 1)

10.713 Rapid Time-Zone Shifts: Effect on Performance and Body Temperature

Key Terms

Body temperature; circadian rhythm; diurnal variation; time-zone shifts

General Description

Flight across six time zones causes a phase desynchronization of human circadian rhythms and time cues in the environment (Fig. 1). In addition, amplitude of the rhythms declines significantly for the first postflight day and normalizes gradually thereafter. Adaptation of circadian rhythms is more rapid for phase delays (westbound flights) than for phase advances (eastbound flights). Complete adjustment of phase for the performance rhythm of a complex psychomotor task requires 12 days for eastbound flights, 10 days for westbound, but adjustment is more rapid for performance of simpler tasks (9 and 6 days, respectively). The adjustment of phase for body temperature rhythm is somewhat slower, requiring 11-12 days following westbound flight and 14-15 days after eastbound flight.

Methods

Test Conditions

- Flight across six time zones (Chicago, Illinois, to/from Frankfurt, West Germany); eastbound flight caused full night's sleep loss; westbound flight caused 2-3 hr sleep loss
- Body temperature (BT) measured by rectal probe carried continuously on test days; performance determined by four tests described below
- Reaction time (RT): visual signal presented 15 times over 3 min in irregular intervals without warning
- Symbol cancellation (SC): standard configurations of three, four, or five dots formed the symbols; 432 symbols in 13 lines randomly distributed on one page printed by computer; signal target was four-dot symbol
- Digit summation (DS): 150 randomly distributed two-digit numbers arranged in ten lines on one page
- Psychomotor performance (PP): for 10 min, subject chose different sized steel balls from reservoir and correctly inserted them into the corresponding size holes of a rapidly revolving cylinder
- All four tests performed nine times per test day at 3-hr intervals from 0900-0900 on the 3 days before outgoing flight and on Days 1, 3, 5, 8, and 13 following each flight; BT, but not performance, was also recorded for Days 2, 4, and 6 after each flight
- On Days 1-6, 8, and 13, subjects were not allowed to leave the hotel

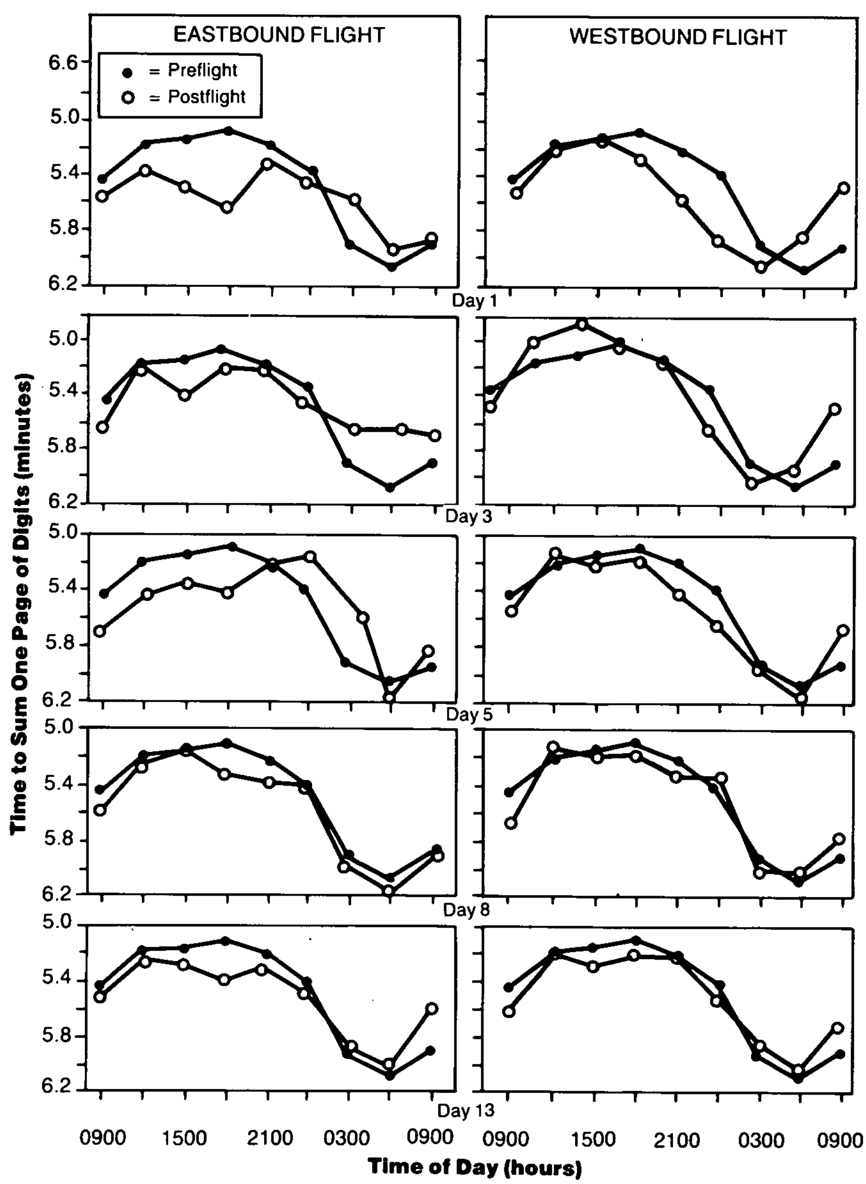

Figure 1. Circadian rhythms for performance of a digit summation task following eastbound and westbound flights (six hours' time difference). (From Ref. 2)

Experimental Procedure

- Independent variables: direction of flight (eastbound or westbound), time of day, postflight day (1, 3, 5, 8, and 13)
- Dependent variable: phase angle difference between preflight and postflight curves for performance tests and body temperature
- Subject's task: for RT task, push button upon signal detection; for SC task, cross out four-dot symbol; for DS task, add each five consecutive numbers horizontally and write down answer; for PP task, insert steel balls into holes of matching size
- 8 male college subjects, 21-26 yr, extensive practice

Experimental Results

- Amplitude of performance rhythms after eastbound flight declines significantly, ~40-70% on postflight Day 1, and normalizes only gradually, between Day 7 for reaction-time (RT) task and Day 13 for psycho-motor performance (PP).
- Amplitude after westbound flight declines less (25-46%) than for the eastbound flight and returns to normal between Day 5 for the digit summation (DS) task and Day 8 for PP.
- After the eastbound flight, the immediate phase desynchronization is between 3.5 hr (BT and PP) and 1.5 hr (RT and DS).
- After the westbound flight, immediate phase desynchronization is less than after the eastbound flight, with the greatest difference being <3 hr.
- The time course of phase adaptation in each task is approximately the same as for amplitude recovery: those tasks showing most rapid readaptation of phase in the performance rhythm also show the most rapid return to preflight amplitude.

Variability

Although individual differences are not detailed, 10-35% of the amplitude depression of the group mean is attributed to individual variation.

Repeatability/Comparison with Other Studies

Similar patterns for readaptation of circadian rhythms after eastbound and westbound travel were demonstrated in German pilots and students, although for them the eastbound flight was the homegoing one (Ref. 1). Similar differences in adaptation to phase advances compared with phase delays are reported for shift-work and altered schedules in isolation experiments (CRef. 10.710).

Constraints

- Round-the-clock testing sessions included awakening subjects for the sessions at 0300 and 0600 hr, and performance may be impaired following arousal from sleep.
- Isolation in the hotel for Days 1-6 after each flight may have slowed adaptation, which is known to be accelerated by immersion in normal activity on the new schedule.

Key References

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Cross References

10.701 Characteristics of biological rhythms;

10.702 Circadian variation in body temperature;

10.707 Circadian variation in work efficiency;

10.710 Adaptation of circadian rhythms to altered schedules;

10.714 Sleep/wake and body temperature cycles during isolation from external time references;

10.802 Sleep deprivation: effect on performance and memory;

10.809 Partial deprivation of sleep: effect on performance

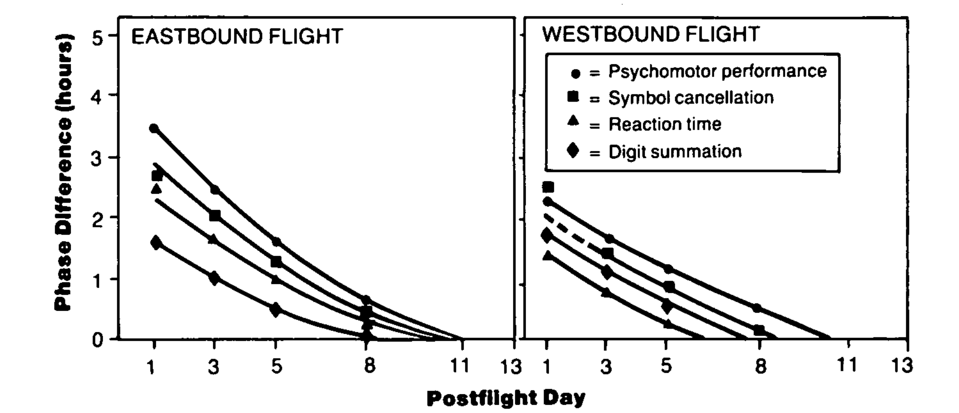

Figure 2. Phase angle differences on four tasks for subjects completing flights across six time zones; the phase angles are given in radians; the reference is 0900 hr, i.e., the mean time of the first test session in the morning; they are estimates of the time when the best-fitting cosine function passes through a maximum. (From Ref. 2)

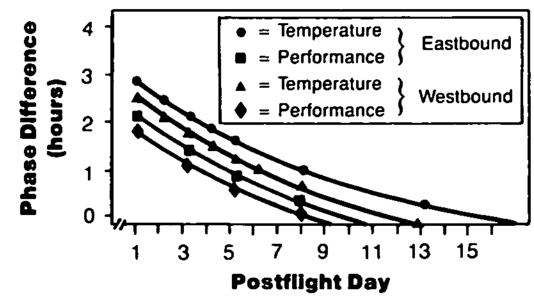

Figure 3. Phase angle differences for body temperature and performance for subjects completing flights across six time zones; the phase angles are given in radians; the reference is 0900 hr, i.e., the mean time of the first test session in the morning; they are estimates of the time when the best-fitting cosine function passes through a maximum. (From Ref. 2)

10.714 Sleep/Wake and Body Temperature Cycles During Isolation from External Time References

Table 1. Period of body temperature and sleep/wake rhythms for 6-month isolation. (From Ref. 1)

	Body Temperature Cycle						Sleep/Wake Cycle	
Month	Number of Cycles Observed	Period Computed from Intervals Between Maximum BT (hr, min)	Standard Deviation (hr, min)	Number of cycles observed	Period Computed from Intervals Between Minimum BT (hr, min)	Standard Deviation (hr, min)	Number of Cycles Observed	Time Between Two Wakenings (hr, min)
June 2-12							12	25, 00
13-30							9	46, 03
2-30	20	24, 42	2, 05	20	24, 27	1, 32	21	34, 02
July 1-13							7	45, 59
14-31							15	27, 34
1-31	10	24, 13	1, 30	10	24, 09	1, 29	22	33, 25
August	10	24, 30	3, 02	9	24, 07	4, 07	27	27, 25
September	3			2			28	25, 46
October	30	24, 48	2, 07	30	24, 48	4,23	30	24, 39
November	9	24, 03	1, 47	11	23, 31	4, 20	23	31, 21
Total	82	24, 31	2, 25	82	24, 21	3, 04		

Key Terms

Body temperature; circadian rhythm; diurnal variation

General Description

During a 6-month isolation from all external time cues, body temperature (BT) maintains a circadian rhythm (~24 hr), varying from a mean periodicity of 24 hr, 28 min for the first 2 months to 24 hr, 44 min for the last 4 months, and varying little in amplitude. Over the same 6-month period, the sleep/wake (SW) cycle is much more irregular. For the first 12 days, the SW cycle remains circadian (25 hr), but for the rest of the first month the mean length of time between two wakenings is 46 hr, 3 min. For the second and third months, the SW cycle continues to be long, and although it resumes a circadian periodicity for the fourth and fifth months, it again lengthens in the sixth month.

Methods

Test Conditions

- From June 2 to November 30 subject isolated in cave 1000 m above sea level; access 70 m deep, lock chamber with trolley isolated the subject from entrance gallery; subject lived in dimly lit tent; surrounding temperature of 6-7°C, raised to 20°C when subject lit heating apparatus; humidity of 100%
- Telephone connection to research team at surface
- BT measured rectally and recorded every half hour
- SW cycle determined based on subject calling to surface before and after each sleep (confirmed in many cases by electroencephalogram)
- Pre- and post-experimental recording of BT carried out for 15 days each; subject showed baseline maximum ~2100 hr with an average value of 37.2°C, minimum ~0400 hr with average value of 36°C; drop faster than rise

Experimental Procedure

- Independent variable: time of day
- Dependent variables: amplitude of BT rhythm; period of BT, measured as interval between two maximum or two minimum temperatures; period of SW cycle, measured as time interval between two consecutive awakenings
- 25-year-old male subject, 1.80 m tall, weighing 75 kg

Experimental Results

- Period of body temperature rhythm was measured in two ways: interval between two maxima or interval between two minima. Results are similar for both measures (Table 1), with slight differences explained by interruptions of recording. In October, when all the cycles were recorded, the same value is found for both measures.
- Calculations of the least-squares slope for the shift of the times of appearance of the maximum and minimum temperatures from real time during June and July (first two months) gives a mean period of 24 hr, 28 min ($r = 0.973 \pm 0.01912$), and for the last four months a mean period of 24 hr, 44 min ($r = 0.9998 \pm 0.00018$), which differs significantly from that of the first two months ($p < .001$).
- Mean maximum BT is 37.2°C (standard deviation 0.3) and mean of minimum BT is 35.8°C (SD 0.3), as amplitude of circadian oscillation calculated for each cycle remains steady (mean 1.4°C).
- Irregularity of SW cycle (Table 1) is so great that only for September and October are cycles consistent enough for the mean data to be useful.

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• For the whole experiment, the frequency distribution of the SW cycle in relation to its length shows two peaks: one ~24 hr and one ~48 hr.

Repeatability/Comparison with Other Studies

BT and SW remain synchronous at 25.7 hr for the first 14 days of isolation, but from then until the end of the 3 months of a single subject's isolation, BT remains circadian (25.1 hr) while SW lengthens to 33.4 hr, longer than the 2028 hr accepted as circadian (Ref. 3). Reference 2 confirms that a circadian rhythm for BT continues while the SW cycle becomes more irregular.

Constraints

• Study does not give information about the relation of the sleeping and waking times to the maximum and minimum of BT, so it is not clear whether subject slept at the low point of a BT cycle as individuals do under normal (nychthemeral) conditions.

• Only one subject was used, making generalization of results very hazardous.

• Relevant only for months where the two rhythms had approximately the same period. For the others, the two minima would have to drift in and out of phase.

Key References

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Cross References

10.701 Characteristics of biological rhythms;

10.702 Circadian variation in body temperature;

10.704 Time of day: effect on memory;

10.705 Time of day: effect on short-term memory and speeded decision making;

10.706 Time of day: effect on speeded decision making;

10.707 Circadian variation in work efficiency;

10.711 Circadian variation in vigilance performance and body temperature for individuals with different work shift preferences;

10.712 Schedule shift: effect on performance;

10.713 Rapid time-zone shifts: effect on performance and body temperature

10.801 Fatigue: Effect on Performance

Key Terms

Cognitive tasks; fatigue; fatigue aftereffects; memory; vigilance

General Description

Although feeling tired is a common experience, it has proved difficult to operationally define fatigue and to study its effects on performance. Fatigue has been variously defined as number of hours of work, hours on duty, hours until subjects could not continue work, and as subjects' self-ratings of fatigue, which may or may not correlate with performance decrements. Fatigue and exhaustion appear to be distinct phenomena.

Tasks which show performance deterioration over time at work, such as continuous vigilance, tend to be repetitive and simple. When more complex tasks are studied, the effects of prolonged work are less direct, less uniform, less general, and less certain. Aftereffects tend to be task-specific, rather than generalized, the two major effects being phasic fatigue (a short-term phenomenon) and aversion to effort. As fatigue increases, skilled subjects seem to lose the smooth coordination of the parts of the task, and attention is allocated less efficiently. The table summarizes areas in which fatigue has been studied, and its effects.

Area	Task or Description	Effect of Fatigue	Source
Physical effort	Pulling on dynamometer handle during trials separated by brief rest pauses	The amount of strength which subjects exert decreases during a prolonged contraction and over a series of trials, but subjects who know that they would get 100-sec rests perform better even on first trial than subject who expect 25-sec rests	Ref. 3
	Continuous movements on finger ergograph as long as possible	Subjects find it impossible to continue long before the task becomes physiologically impossible; subjects led to believe that the weight has been reduced are able to begin the contractions again	Ref. 7
	Hanging from parallel bar as long as possible	Subjects who are promised $5 hang on twice as long as controls and subjects who are encouraged by experimenter	Ref. 9
Perception	Prolonged sensory stimulation	All the senses show habituation or adaptation effects (decline in sensitivity); fatigue effects are usually seen as a decline in alertness rather than in sensitivity	Ref. 7
	Rate of blinking measured in female machinists	Blinking rate correlates well with reported visual fatigue	Ref. 7
	Reading fine print	Performance decrement	Ref. 7
	Vigilance, both visual and auditory	Decreases in number of correct detections are usually associated with greater caution in setting criterion	CRef. 7.403
		Some evidence of decrement in sensitivity at high event rates on certain tasks	CRef. 7.408
Skilled performance	Simulated cockpit studies	Larger deviations of instrument reading are tolerated before corrective action is taken	Ref. 1
		Lapses in attention (phase fatigue) are more frequent	
		Distraction increases	
		Selectivity increases: items of central importance are attended to while peripheral items are neglected	
		Responses become more variable	
		Timing is off	
		Performance pattern loses cohesion	

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Area	Task or Description	Effect of Fatigue	Source
Skilled performance (cont.)	Flying and driving	Evidence is contradictory: some studies show specific decrements, some do not; some even show certain improvements. Studies require considerable driving or flying; subjects improve through practice	Ref. 7
	Film records of skilled runners	Running becomes slower because of a reduction in stride length	Ref. 2
		Changes in movement patterns do not follow a uniform decrease	
	Four cognitive tasks	Performance falls for one, improves for one, is unchanged for two	Ref. 7
Aftereffects	200 sec of strenuous exercise (one foot up and down each second of Harvard step task)	On following cognitive task, no difference between rested and fatigued subjects	Ref. 4
	Pedal bicycle ergometer for 15-20 sec, or for 2, 5, or 10 min	Improvement on detection task involving short-term memory, except after 5 or 10 min	Ref. 4
	Manual cranking of ergometer, light versus heavy exercise	Accurate reciprocal tapping is facilitated by light exercise	Ref. 5
		Tapping scores are depressed by heavy exercise only with the fatigued arm	
Phasic fatigue	Self-paced tasks during 65-hr sleep deprivation	Increasing variance in reaction time	Ref. 11 CRef. 10.802
		Increasing frequency of very long reaction times	
	Experimenter-paced tasks during 65-hr sleep deprivation	Increase in omission errors	
Aversion	After 24-32 hr of continuous work on vigilance and cognitive tasks	Fatigued subjects are more likely to choose low effort/low probability of success strategies over high effort/high probability option	

Constraints

- Fatigue is not so clearly differentiated from sleep loss here, nor from time on the job/task, e.g., in skilled performance portion of table.
- Sufficient motivation can overcome many of the effects of fatigue, and real life experiences may generate higher motivation than experimental tasks.

Key References

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Cross References

7.403 Decline in rate of correct detection of signals over time (vigilance decrement);

7.408 Effect of event rate on vigilance performance;

10.802 Sleep deprivation: effect on performance and memory

10.802 Sleep Deprivation: Effect on Performance and Memory

Key Terms

Cognitive tasks; communications; concurrent tasks; memory; reaction time; recall; serial responding; sleep deprivation; vigilance

General Description

The effect of total, partial, or selective sleep deprivation on performance is often studied, although partial and selective deprivation cannot be separated operationally in terms of response (CRef. 10.809). In total sleep deprivation, subjects are not allowed to sleep at all for one or more nights. In general, significant amounts of sleep loss lead to greater variability and increased deficit in performance, a neglect of task priorities or an inability to direct attention selectively, and impairment of active working memory (but not passive holding capacity).

The longer the sleep deprivation, the earlier in the task an effect appears, and the longer the task, the greater the effect of the deprivation, especially on tasks with unchanging stimuli and responses. The table lists tasks, the usual impairment, amount of sleep loss, and comments (which indicate conflicting results or describe unfamiliar tasks) for subject-paced, experimenter-paced, and memory tasks.

Task Type	Task Description	Sleep Loss	Effect	References
Subject-paced				
Reaction time		30-78 hr	Mean markedly increases, strongly related to increasing hr of sleep loss; (effect doubles between 30 and 78 hr) Mean is an increasing monotonic function of task duration Mean increase caused by slight overall increase in duration and frequency of long response times Breaks in task or change in stimuli or response causes above effects to appear only in later portions of task	Ref. 2
Serial response		After only 32 hr	Number of correct responses reduced Number of errors increases only in final 10 min of 30-min session Increased number of long responses (>1.5) Impairment reduced by noise and knowledge of results	Ref. 1 CRef. 10.805
Adding		Even after 86 hr	Percentage correct shows minimal change	Ref. 2
		After only 48 hr	Number of sums attempted decreases significantly	
Communication (sending)	Make tape recording describing to second subject how to place pieces in a pattern	7 hr	Number of pieces described incorrectly does not significantly increase Number of errors made and corrected increases significantly Time taken in describing pattern and pieces shows progressive, significant increase (effect doubles from 0-7 hr)	Ref. 2
Communication (receiving)	Construct pattern described on tape recording		Errors of commission increase	Ref. 2

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Task Type	Task Description	Sleep Loss	Effect	References
Concept attainment	Card array with borders and geometrical designs; figure, number of figures, borders, and color vary; subject shown one exemplar of concept, must choose cards for yes-no response to discover concept	After 72-81 hr	Slight decrease in number solved Time per solved problem significantly increases, range 16-71% 2 or 12 subjects show no increase in time per problem	Ref. 2
Prediction of probability	Predict whether left- or right-hand slot machine key will deliver token; delivery random at 50-50 probability; measures variety of run-hypotheses formed; larger predictability, fewer hypotheses used	After only 28 hr	Predictability measure increases; reflects change in quality of performance	Ref. 2
Experimenter-paced				
Vigilance (visual, auditory, cutaneous)		24-98 hr	Both types of errors increase; errors of omission (misses) increase much more than errors of commission (false alarms) The greater the sleep loss, the earlier in the task a vigilance decrement occurs The greater the sleep loss, the greater the vigilance decrement With knowledge of results, impairment is slightly less With exhortation to do better, impairment is significantly less in some cases, but only slightly less in others	Ref. 2
Dual task	Primary task: tracking; secondary task: signal detection of lights arranged in semi-circle; central lights close to tracking window, peripheral lights at edges of visual field	30 hr	Increased decrement Less efficiency for tracking task over time, especially in last 20 min of 40-min session Reduction of normally pronounced difference of central and peripheral lights Decreases selectivity, or ability to direct attention	CRef. 10.806
Memory				
Information learning	Answers to questions committed to memory	28-76 hr	Immediate recall: impairment; decline continues as sleep loss increases	Ref. 2
		At 28 hr	Delayed recall (after 24 hr): same accuracy as immediate recall	
		After 51 hr	Delayed recall markedly poorer than immediate recall; does not decline as steadily as sleep loss increases	
Word list recall		1 night's sleep	When words presented before sleep loss, recall after sleep recovery is not impaired When words presented after sleep loss, recall after sleep recovery is impaired	Ref. 3

Constraints

- Sleep loss appears to be a de-arouser, so that task's interest or complexity and other task characteristics that may cause arousal can attenuate the types of impairment discussed here for simpler tasks.

Key References

1. Wilkinson, R. T. (1957). *Effects of lack of sleep* (FPRC Rep. No. 9613). Cambridge, England: Medical Research Council.

*2. Williams, H. L., Lubin, A., & Goodnow, J. J. (1959). Impaired performance with acute sleep loss. *Psychological Monographs, 73*, 1-26.

3. Williams, H. L., Gieseking, C. F., & Lubin, A. (1966). Some effects of sleep loss on memory. *Perceptual and Motor Skills, 23*, 1287-1293.

Cross References

10.703 Cyclical patterns of sleep;

10.801 Fatigue: effect on performance;

10.803 Sleep deprivation: effect on reaction time in a two-choice task;

10.804 Sleep deprivation: effect on serial responding;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.806 Sleep deprivation: effect on performance of a dual task;

10.808 Sleep deprivation: effect on circadian rhythm;

10.809 Partial deprivation of sleep: effect on performance

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

10.803 Sleep Deprivation: Effect on Reaction Time in a Two-Choice Task

Key Terms

Phasic fatigue; reaction time; sleep deprivation; vigilance

General Description

After total sleep deprivation for 78 hr, subjects' reaction times in a two-choice serial reaction task increase slightly overall. The greatest performance decrements are the lengthening of the slowest reaction times and an increase in the number of slow reaction times during sleep deprivation. Such lapses are attributed to phasic fatigue.

Methods

Test Conditions

- Subject seated at center of table, fixated blacked-out center light; two side lights 58.42 cm from center from table, with two corresponding response keys; a click from loudspeaker warned subject that one of two side lights would be turned on in 2 sec; pressing appropriate key turned out light
- 11-day cycle of sleep deprivation: Days 1-4 baseline, normal sleep/wake schedule; Days 5-8 sleep loss, sleep deprivation levels of none, 30, 54, 69 and 78 hrs; Days 9-11 recovery, normal sleep/wake schedule

Experimental Procedure

- Two-choice serial reaction task
- Independent variable: sleep deprivation
- Dependent variables: reaction time (detection latency) from signal target onset to depression of correct response button, number of lapses (reactions taking at least twice as long as mean baseline response)
- Subject's task: depress response button as quickly as possible corresponding to lighted side light
- 50 enlisted men (19-22 yrs) and 24 religious conscientious objectors (18-54 yrs)

Experimental Results

- After 78-hr sleep loss, mean reaction time is twice as long as on the last baseline day; increase in mean reaction time is directly related to increasing hours of sleep loss.
- During sleep loss, on some trials subjects come close to their baseline performance ($p < 0.05$) (see average of ten shortest reaction times in Fig. 1a).
- During sleep loss, duration of long reaction times increases significantly ($p < 0.05$) (see average of ten longest reaction times in Fig. 1a).
- The frequency of very long reaction times also increases with sleep loss ($p < 0.05$) (see Fig. 1b).

Variability

Significance was determined by Spearman rank order coefficient and Kendall tau rank order coefficient.

Repeatability/Comparison with Other Studies

On other reaction-time tasks, the same patterns of results are described (Ref. 2), but duration of task and breaks or pauses influence when patterns of lapses occur. Number of gaps (reaction times >1.5 sec) on five-choice serial response task also increases with sleep deprivation (Ref. 1).

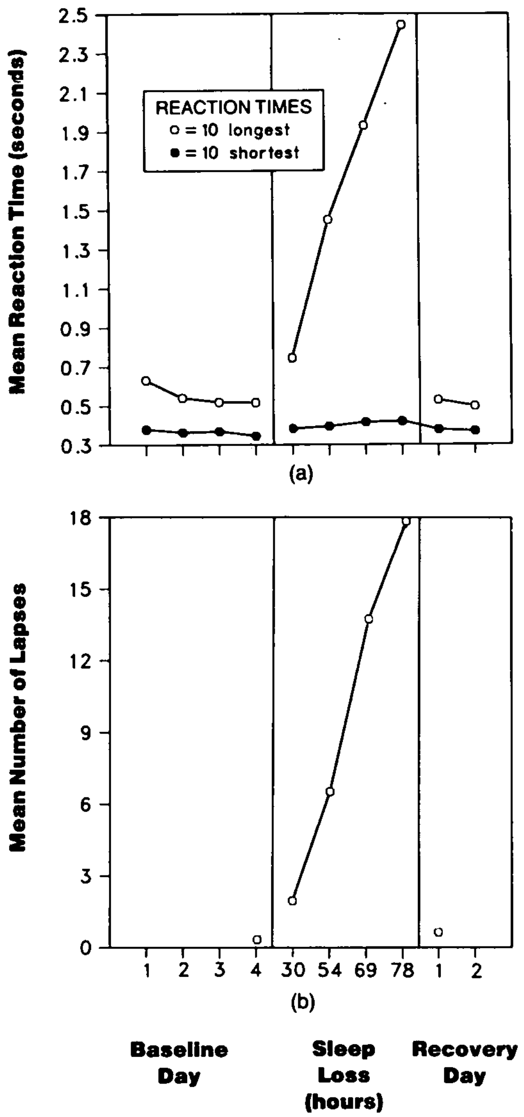

Figure 1. Changes in choice reaction time during four days of sleep loss; (a) mean reaction time, (b) mean number of lapses (responses taking at least twice as long as baseline response time) during four baseline days, four days of sleep loss, and two recovery days. (From Ref. 2)

Constraints

- Although described as a self-paced task, the onset of the cue and the signal were not under subject control.
- Errors are not described.
- Results may be difficult to generalize to other types of tasks.

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Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Wilkinson, R. T. (1963). Interaction of noise with knowledge of results and sleep deprivation. *Journal of Experimental Psychology, 66*, 332-337.

*2. Williams, H. L., Lubin, A., & Goodnow, J. J. (1959). Impaired performance with acute sleep loss. *Psychological Monographs, 73*, 1-26.

Cross References

9.105 Speed-accuracy tradeoffs;

9.111 Choice reaction time: effect of number of alternatives;

9.112 Choice reaction time: effect of probability of alternatives;

10.103 Classification of factors influencing the stress state;

10.801 Fatigue: effect on performance;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.808 Sleep deprivation: effect on circadian rhythm;

10.809 Partial deprivation of sleep: effect on performance;

Handbook of perception and human performance, Ch. 44, Sect. 3.5

10.804 Sleep Deprivation: Effect on Serial Responding

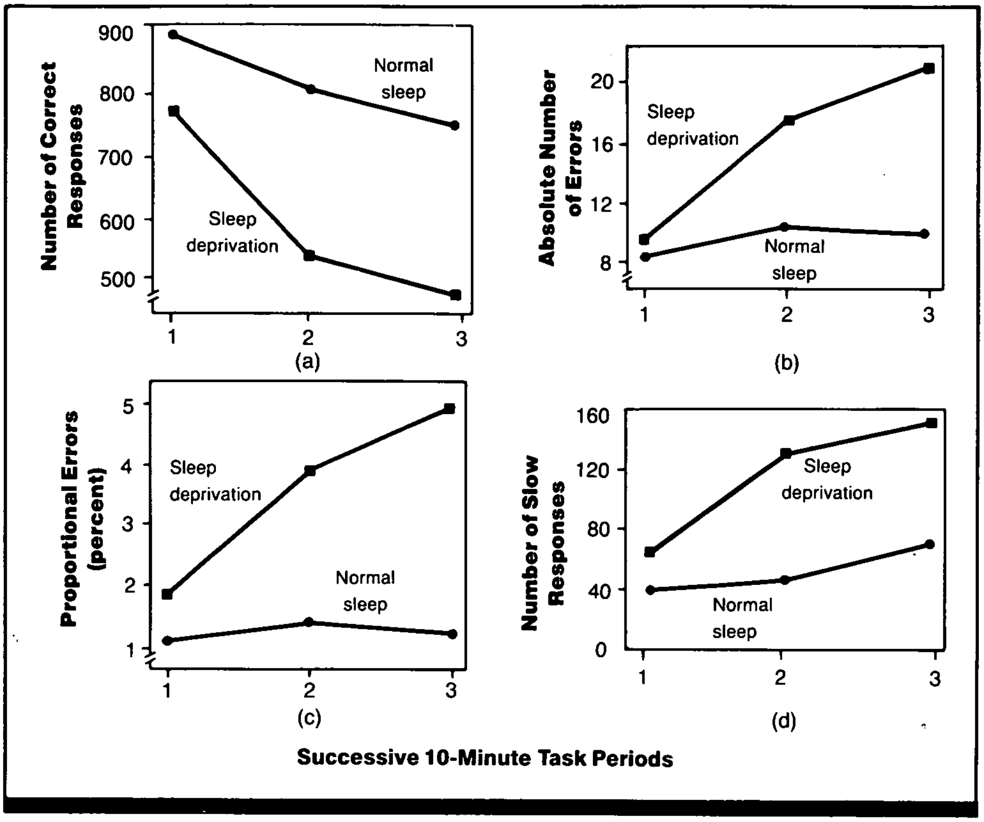

Figure 1. The effect of normal sleep and sleep deprivation on performance of a serial response task. (From Ref. 3)

Key Terms

Reaction time; serial responding; sleep deprivation

General Description

On a self-paced five-choice serial response task, approximately 32 hrs without sleep reduces the number of correct responses made in each 10-min period of the 30-min task and increases the number of slow responses (response times longer than 1.5 sec.)

Methods

Test Conditions

- Five neon light bulbs forming a pentagon. Each bulb can be turned off by the touch of a stylus
- Bulbs normally unlighted; when one is lighted randomly, subject touches corresponding contact to turn it off
- Subjects in sleep deprivation condition were tested after 32 hrs of no sleep
- Each subject served in both normal sleep and sleep deprivation conditions 2 days apart

Experimental Procedure

- Five-choice serial response task; order counterbalanced
- Independent variable: rest condition
- Dependent variables: number of signal targets detected correctly; absolute number of errors (wrong contact touched); proportional errors (percentage of total responses); number of slow responses (latencies >1.5 sec); all values averaged for each 10-min period of 30-min task
- Subject's task: detect lighted bulb and touch corresponding contact
- 12 subjects, enlisted men (18-30 yr), all had experienced 3 hr of the five-choice serial reaction task to measure other variables

Experimental Results

- Sleep loss significantly reduces the number of correct detections ($p<0.01$) (Fig. 1a).
- With sleep deprivation, the absolute number of errors does not increase significantly (Fig. 1b); however, fewer total responses are made, which results in a rise in the proportion of errors ($p<0.001$) (Fig. 1c).
- Sleep loss significantly increases the number of responses with latencies > than 1.5 sec ($p<0.01$) (Fig. 1d).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Similar effects of sleep loss are reported for vigilance performance with auditory and visual signals (Refs. 1, 2).

Constraints

- Since order of presentation of conditions was counterbalanced, analysis of possible order effects was not possible.
- Noise and incentives interact with effects of sleep loss.

Key References

1. Wilkinson, R. T. (1959). Rest pauses in a task affected by lack of sleep. *Ergonomics, 2*, 373-380.

2. Wilkinson, R. T. (1960). The effect of lack of sleep on visual watch-keeping. *Quarterly Journal of Experimental Psychology, 12*, 36-40.

*3. Wilkinson, R. T. (1963). Interaction of noise with knowledge of results and sleep deprivation. *Journal of Experimental Psychology, 66*, 332-337.

Cross References

7.801 Effect of incentives on performance;

10.305 Continuous open-field white noise: effect on speed/accuracy tradeoffs in serial response tasks;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.809 Partial deprivation of sleep: effect on performance

10.805 Five-Choice Serial Response Task: Effect of Different Stressors on Performance

Variable/ Stressor	Description and Second Stressor	Performance Measure: Number of Correct Responses	Performance Measure: Number of Errors	Performance Measure: Response Time	Sources
Fatigue	30 min with no breaks	decrease	increase	increase	Refs. 1, 2, 3, 4, 6, 7, 8, 9, 10, 11
Noise	90-100 dB steady broadband sound		increase		Refs. 3, 4, 6, 10 CRef. 10.305
	alcohol		interaction		Ref. 4
	incentive		interaction	interaction	Ref. 9
Sleep loss	One complete night without sleep	decrease	increase	increase	Refs. 6, 7, 8, 9, 10, 11 CRef. 10.804
	alcohol		interaction		Ref. 11
	incentive		counteraction	counteraction	Ref. 9
	noise	counteraction	counteraction	counteraction	Refs. 6, 10
	L-hyoscine (sedative)				Ref. 5
	heat				Ref. 7
Incentives	Augmented feedback and competition	increase	decrease	decrease	Refs. 9, 10, 11
	alcohol		interaction		Ref. 11
Heat	30° C effective temperature		increase	increase	Ref. 7
Alcohol	0.21 or 0.42 mg/kg		increase		Refs.4, 11
Hyoscine (sedative)	0.7 mg L-hyoscine	decrease		increase	Ref. 5
Time of day	Testing at later times in the day	increase		decrease	Ref. 1

Key Terms

Fatigue; five-choice serial response; heat; incentive; noise; sleep deprivation; stressors; time of day

General Description

In a five-choice serial response task, five neon bulbs form a pentagon. Each bulb can be turned off by the touch of a stylus. The subject monitors the bulbs, which are lighted one at a time in a random pattern, and turns off the lighted bulb with the stylus to indicate detection of the lighted bulb. Turning off any bulb alters the display, making the task self-paced and continuous. This continuous attention demand makes performance on the task susceptible to stressors. The numbers of correct responses, errors, and long response times (> 1.5 sec) are measured, allowing speed, accuracy, and phasic fatigue to be addressed.

The table lists stressors and their effects on performance. The second column defines the stressor and/or lists a second stressor which is present along with the first. The effect of the stressor on three performance measures is given. In the case of two stressors, whether the second interacts to increase the effect of the first or counteracts that effect (i.e., produces opposite effect of first stressor alone) is indicated. Empty cells indicate that no consistent effect of the stressor on that performance measure has been found.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Blake, M. J. F. (1967). Time of day effects in performance on a range of tasks. *Psychonomic Science, 9,* 349-350.

2. Blake, M. J. F. (1971). Temperament and time of day. In W. P. Colquhoun (Ed.), *Biological rhythms and human performance* (pp. 109-145). London: Academic Press.

3. Broadbent, D. E. (1953). Noise, paced performance and vigilance tasks. British *Journal of Psychology, 44,* 295-303.

4. Colquhoun, W. P., & Edwards, R. S. (1975). Interaction of noise with alcohol on a task of sustained attention. *Ergonomics, 18,* 81-87.

5. Colquhoun, W. P., & Wilkinson, R. T. (1968). *Interaction of L-hyoscine and sleep deprivation.* Unpublished manuscript, MCR Applied Psychology Unit, Cambridge, England.

6. Corcoran, D. W. J. (1962). Noise and loss of sleep. *Quarterly Journal of Experimental Psychology, 14,* 178-182.

7. Pepler, R. D. (1959). Warmth and lack of sleep: Accuracy or activity reduced. *Journal of Comparative and Physiological Psychology, 52,* 446-450.

8. Wilkinson, R. T. (1959). Rest pauses in a task affected by lack of sleep. *Ergonomics, 2,* 373-380.

9. Wilkinson, R. T. (1961). Interaction of lack of sleep with knowledge of results, repeated testing and individual differences. *Journal of Experimental Psychology, 62,* 263-271.

10. Wilkinson, R. T. (1963). Interaction of noise with knowledge of results and sleep deprivation. *Journal of Experimental Psychology, 66,* 332-337.

11. Wilkinson, R. T., & Colquhoun, W. P. (1968). Interaction of alcohol with incentive and sleep deprivation. *Journal of Experimental Psychology, 76,* 623-629.

Cross References

10.201 Types of tasks used in measuring the effects of stress, fatigue, and environmental factors on performance;

10.305 Continuous open-field white noise: effect on speed/accuracy tradeoffs in serial response tasks;

10.310 Continuous broadband noise: performance-related aftereffects of exposure;

10.804 Sleep deprivation: effect on serial responding

10.806 Sleep Deprivation: Effect on Performance of a Dual Task

Key Terms

Concurrent tasks; sleep deprivation; tracking; vigilance; vigilance decrement

General Description

Subjects performing a tracking task, defined as the primary task, and a signal detection task, defined as secondary, show less efficiency for the tracking task over time (vigilance decrement). This decrement increases, especially in the last 20 min of a session, after 30 hr of sleep loss. Sleep deprivation also reduces the normally pronounced difference in reaction times in response to centrally versus peripherally located lamps in the vigilance task. Sleep loss produces a tendency to neglect task priorities or to fail to allocate attention appropriately.

Methods

Test Conditions

- Tracking window centered in the visual field; arc of six lamps at angles of 20, 50, and 80 deg from center, all 80 cm from subject
- Target pointer moved from side to side in window by irregularly shaped cam
- Second pointer, to be kept aligned with the target, controlled by a handle moved in the vertical plane by subject's right hand
- Secondary task, signal target: 600-msec light flashes (luminance adjusted to satisfy a performance criterion of 50% detection), presented randomly with average of 6 per min, with relative frequency across locations of 1-1-4-4-1-1, so that central sources had four times as many signals as did peripheral sources
- Panel with six response buttons, one for each light, under subject's left hand
- Background of 70 dB broadband noise
- Sleep condition: normal or one night without sleep
- Subjects served in two 40-min sessions a week apart; half had normal sleep first, sleep deprived second; other half had reversed order

Experimental Procedure

- Dual vigilance task
- Independent variables: amount of sleep, location of lamp in semicircular visual field
- Dependent variables: for primary task, integrated time on target (TOT) over successive 10-min periods, expressed as proportion of maximum (600 sec); for secondary task, detection times for each light source
- Subject's task: for primary pursuit tracking, keep pointer aligned with moving target pointer by manual control of lever; for secondary task: detection of light flash, press button corresponding to light that flashed
- 12 subjects, naval personnel 17-23 yr, some practice

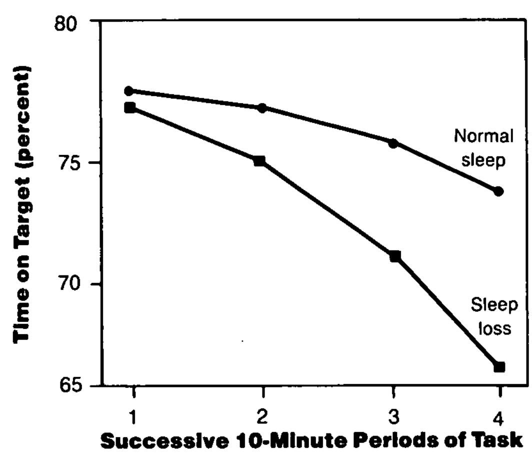

Figure 1. Percentage of time on target in successive 10-min periods of the task for normal-sleep and sleep-deprived subjects. (From Ref. 1)

Experimental Results

- Mean time on target (TOT) scores decrease significantly ($p < 0.05$) from the first to the fourth 10-min period for the normal sleep condition.
- The decrement in TOT is significantly greater ($p < 0.01$) in the sleep deprivation condition (Fig. 1).
- Sleep deprivation causes an overall increase in detection time for the secondary task, especially in the last two 10-min periods of the task.
- Sleep deprivation also diminishes the absolute difference usually found between mean detection time for the central (3 and 4) and for the peripheral sources (1, 2, 5, and 6), especially in the last two 10-min periods of the task (Fig. 2).

Variability

Significance was determined by the Wilcoxon *T* test.

Repeatability/Comparison with Other Studies

A similar loss of selectivity with sleep deprivation is reported in a multisource sampling task (Ref. 2). Impairment of vigilance performance on the five-choice serial reaction task as a result of sleep deprivation has been reported (Ref. 3).

Constraints

- There was a small order effect; with sleep loss first, performance a week after normal sleep was not as efficient as when normal sleep was the first condition experienced. Transfer in the other direction also occurred.
- Noise, incentives, and other stressors interact with the effects of sleep loss.

Key References

*1. Hockey, G. R. J. (1970). Changes in attention allocation in a multicomponent task under loss of sleep. *British Journal of Psychology, 61*, 473-480.

2. Hockey, G. R. J. (1973). Changes in information selection patterns in multisource monitoring as a function of induced arousal shifts. *Journal of Experimental Psychology, 101*, 35-42.

3. Wilkinson, R. T. (1963). Interaction of noise with knowledge of results and sleep deprivation. *Journal of Experimental Psychology, 66*, 332-337.

Cross References

10.304 Continuous noise: effect on a dual vigilance task;

10.809 Partial deprivation of sleep: effect on performance

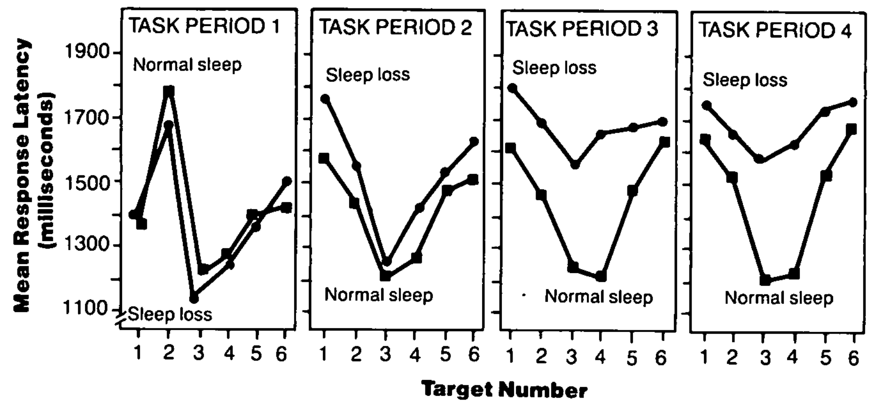

Figure 2. Mean response latency in successive 10-min periods of the task as a function of target location for normal-sleep and sleep-deprived subjects. Targets 1 and 6 offset from center of visual field by 80 deg, targets 2 and 5 by 50 deg, and targets 3 and 4 by 20 deg. (From Ref. 1)

10.807 Sleep Deprivation: Use of Physiological Indicators to Predict Performance Decrement

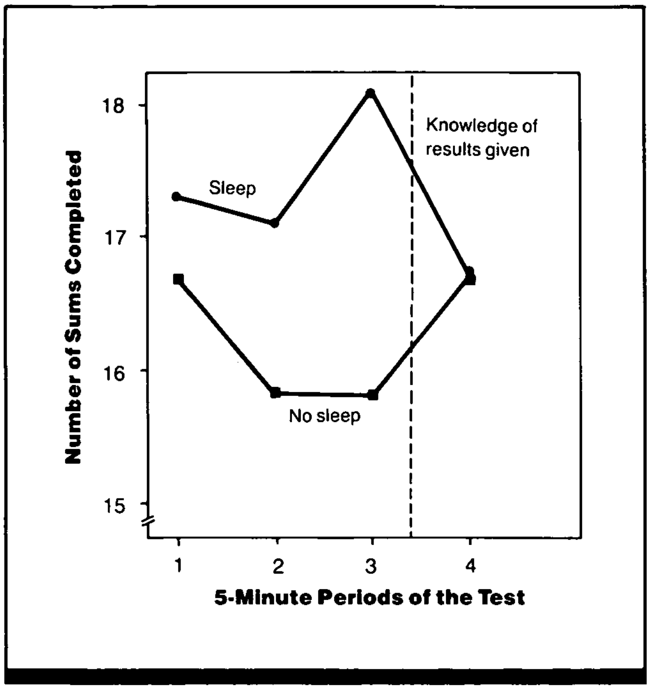

Figure 1. Number of sums completed as a function of test segment for subjects with normal sleep and loss of sleep. Dotted line divides periods with no feedback from periods with feedback. (From Ref. 3)

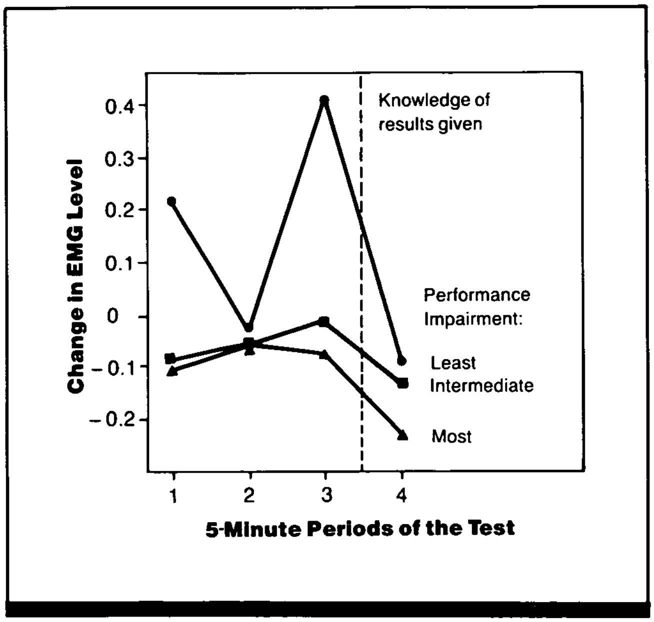

Figure 2. Change in EMG level as a function of test segment for sleep-deprived subjects grouped by magnitude of performance impairment as determined by speed of performance. (From Ref. 3)

Key Terms

Electromyogram; operator selection; sleep deprivation; stress

General Description

Subjects who are deprived of sleep for 32 or 56 hr vary in speed of performance on an adding task. Subjects whose speed of performance is less affected by sleep loss have higher levels of muscle tension compared to their own resting level than do subjects whose speed deteriorates sharply with sleep deprivation. In fact, the difference between resting and working electromyograms (EMG) predicts the degree of performance decrement caused by sleep loss.

Methods

Test Conditions

- Subjects completed 20-min addition task twice, once with normal sleep and once with sleep loss of 32 or 56 hr, 2 or 4 days apart
- Each session preceded and followed by 2 min of relaxation, with EMG recording
- Sheet of 100 sums consisting of five two-digit numbers to be added, two different versions
- EMG records were taken from the *pronator teres* muscle of the left (inactive) forearm hanging loosely at the subject's side; a single channel machine with input impedance of 250 KΩ; pulses reflecting integrated output were recorded on one channel of a tape recorder while the proceedings in the test cubicle were recorded by microphone on the other channel
- Bipolar sponge electrodes attached through two holes in an adhesive patch, left in place to ensure same recording spot under both normal sleep and sleep loss conditions; reasonably equal and low resistance (between 10 KΩ and 3 KΩ) from each electrode to the reference electrode on the active forearm
- Order of presentation of test version and sleep condition balanced
- Feedback of adding test results given after first 15 min of each session and during last 5 min

Experimental Procedure

- Independent variables: sleep condition, feedback of results
- Dependent variables: speed; number of sums completed in 20-min session (averaged for each 5-min period); accuracy (number of errors similarly averaged); EMG level, defined as the ratio of the average EMG during each 5-min period of the 20-min test to the average during the preliminary 2-min period of relaxation
- Subject's task: add as many sums as possible, write down each answer, and announce it verbally
- 12 subjects, enlisted men, ages 18-30 yr, some practice

Experimental Results

- During 15 min of test with no knowledge of results, sleep deprivation has no effect on errors, but significantly reduces the number of sums completed (Fig. 1) when corrected for the interaction between practice and order of presentation ($p < 0.01$).
- With knowledge of performance accuracy, performance with sleep deprivation is the same as with normal sleep (see last 5-min period, Fig. 1).

• The EMG level (increased muscle tension) is highest for subjects showing the least impairment in speed of performance (Fig. 2).
• Increased level of EMG due to loss of sleep correlates negatively with speed ($p < 0.05$) and accuracy ($p < 0.10$) of performance: with more sleep loss, speed and accuracy both decrease.
• Lack of sleep has little effect upon the level of EMG, but increases EMG variability.

Variability

Significance was determined by Kendall's rank correlation coefficient, tau.

Repeatability/Comparison with Other Studies

Other physiological measures show similar patterns with other tasks. High output of adrenaline (and sometimes noradrenaline) is associated with efficient performance under stress (Ref. 1). With parachute trainees, blood plasma parameters (cortisol, catecholamines, testosterone, glucose, growth hormone, and free fatty acids) initially show marked changes followed by a gradual return to baseline, as training continues; such change is also associated with self-evaluations of efficient coping (Ref. 2).

Constraints

• Results apply to only one form of activity and may not generalize to other types of task, particularly those for which the motivation to perform well is high.
• Differences between 32- and 56-hr sleep deprivation conditions are not discussed.

Key References

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2. Ursin, H., Baade, E., & Levine, S. (1978). *Psychobiology of stress: A study of coping men*. New York: Academic Press.

*3. Wilkinson, R. T. (1962). Muscle tension during mental work under sleep deprivation. *Journal of Experimental Psychology, 64*, 565-571.

Cross References

7.804 Effect of stress on performance for introverts and extroverts;

10.101 Theories of arousal and stress;

10.104 Arousal level: effect on performance;

10.305 Continuous open-field white noise: effect on speed/accuracy tradeoffs in serial response tasks;

10.801 Fatigue: effect on performance;

10.805 Five-choice serial response task: effect of different stressors on performance

10.808 Sleep Deprivation: Effect on Circadian Rhythm

Key Terms

Circadian rhythm; diurnal variation; fatigue; periodicity; sleep deprivation

General Description

In the absence of external time cues, subjects totally deprived of sleep show increasing performance deficits on a shooting task and increased subjective ratings of fatigue over a 3-day period. Even in the absence of a sleep/wake cycle, circadian rhythms persist for fatigue and performance. The estimated crests of the circadian rhythm for fatigue ratings occur at ~0300-0500 hr, and the amplitude of the rhythm decreases with sleep deprivation. Performance rhythm is less clear cut, but tends to crest when the fatigue cycle is low and to be low when the fatigue cycle crests.

Methods

Test Conditions

- From Tuesday morning until Friday afternoon (75 hr), subjects sat on chairs at all times except when voiding, saw no daylight, had no clocks or watches; the first 3-hr period was a control period of relaxation; subsequent time was divided into 25 three hour periods
- For first 2.75 hr of each 3-hr period, subjects were exposed to conditions simulating some of the elements of ground combat, including performance on a shooting range (firing an electronic rifle at small targets containing photodiodes); during alternate periods, overhead lamps were lit, or weak footlights near target area were the only illumination
- For the last 15 min of each 3-hr period (25 times total), subjects emptied bladder, drank 300 ml of tap water, and were served two sandwiches; while eating subjects filled out fatigue rating forms

Experimental Procedure

- Independent variables: amount of sleep deprivation, time of day
- Dependent variables: number of shots fired, averaged for 3-hr periods; number of hits (data not shown in Fig. 1); fatigue score
- Subject's task: sit in chair, perform simulated firing range task, and complete fatigue rating form
- 31 male subjects, officers and corporals (ages 20-44, mean 29 yr) in excellent health; non-smokers or smokers who gave up smoking for experiment

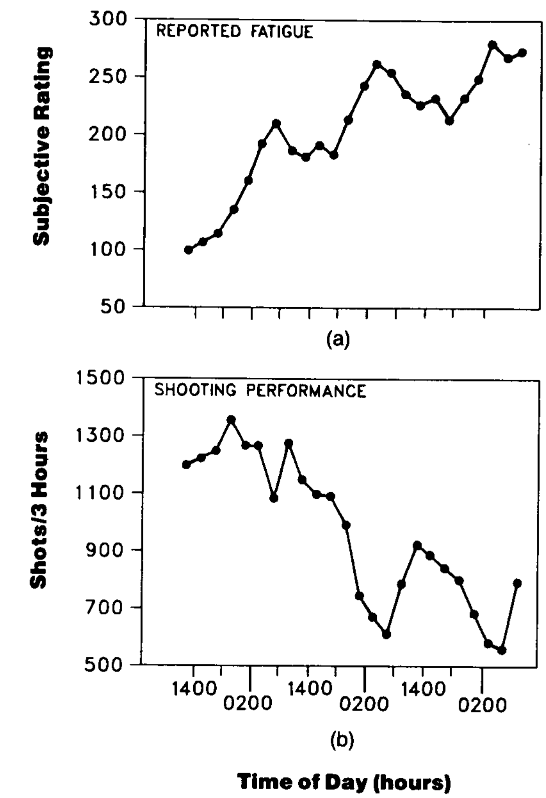

Figure 1. (a) Self ratings of fatigue and (b) shooting performance during 75 hours of sleep deprivation. (From Ref. 1)

Experimental Results

- Shooting performance data fit poorly to a cosine function (chi-square values between 11 and 47, $p < 0.05$ that data fit a cosine function).
- Performance decreases significantly over days, and its estimated crest varies from 1500-2100 hr.
- Number of shots and hits correlate negatively with subjective fatigue rating ($p < 0.001$).
- Fatigue ratings exhibit a circadian rhythm with estimated crests at 0300-0500 hr.
- Fatigue increases significantly over days, while peak of fatigue amplitude tends to decrease over days.

Repeatability/Comparison with Other Studies

Telephone operators exhibit circadian rhythms in performance without sleep deprivation (CRef. 10.707). Reference 2 reports circadian variation in performance during sleep deprivation. Performance deficits with sleep deprivation occur on several types of tasks. Under sleep deprivation, body temperature and fatigue ratings correlate negatively: the more the fatigue, the lower the body temperature (Ref. 3).

Constraints

- Since mean performance measures could not be fitted to a cosine curve, individual variation may be more important than the study recognizes.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Froberg, J., Karlsson, C. G., Levi, L., & Lidberg, L. (1972). Circadian variations in performance, psychological ratings, catecholamine excretion and urine flow during prolonged sleep deprivation. In. W. P. Colquhoun (Ed.), *Aspects of human efficiency: Diurnal rhythm and loss of sleep*. London: English Universities Press.

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3. Murray, E., Williams, H., & Lubin, A. (1958). Body temperature and psychological ratings during sleep deprivation. *Journal of Experimental Psychology, 56*, 271-273.

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Cross References

7.417 Effect of boredom on detection efficiency;

10.701 Characteristics of biological rhythms;

10.702 Circadian variation in body temperature;

10.707 Circadian variation in work efficiency;

10.711 Circadian variation in vigilance performance and body temperature for individuals with different work shift preferences;

10.801 Fatigue: effect on performance;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.807 Sleep deprivation: use of physiological indicators to predict performance decrement;

Handbook of perception and human performance, Ch. 44, Sect. 4.2

10.809 Partial Deprivation of Sleep: Effect on Performance

Sleep Loss	Effects	Source
Partial		
Reduced normal (7.5 hr to 0-6 hr) for 1-9 nights	Progressive effects occur after one night with <2 hr sleep; but with ration <5 hr, effect shows after second night	Ref. 3
	Interacts with duration of task (as does total deprivation)	
	6 hr almost as beneficial as 7.5 hr	
	Small amount of sleep better than none; little difference between 1.5 hr and 3 hr	
	Impairs vigilance detection and calculation rate	
	For first 3 days, sleep loss correlates negatively with running digit span task	
First versus second half of night	Loss of first half night's sleep increases forgetting	Ref. 6
	Loss of second half results in same recall as being awake between presentation of material and recall	
8 days of 3 hr per night	SWS increases proportionally to maintain normal daily ration, causing loss of REM and Stages 1 and 2	Ref. 4
	SWS is lost until ration drops below 3-4 hr, when REM is also likely to be affected	Ref. 3
Selective		
REM deprivation	REM deprivation increases forgetting for semantic material	Ref. 2 CRef. 10.810
	No differences between REM loss and loss of other stages of sleep	Refs. 1, 6

Key Terms

Rapid eye movement; sleep deprivation; sleep stages; slow wave sleep

General Description

The effects of limited rations of sleep (total [CRef. 10.802], partial, and stage-specific sleep deprivation) on performance are usually compared to performance with the normal 7.5-hr sleep. Studies of partial sleep deprivation generally focus on the relative effects of different rations of sleep and the number of nights of such rations required to cause a noticeable difference in performance, rather than on the kinds of performance deficits produced.

Selective Sleep Deprivation

During a given night's sleep, sleep stages show a periodicity of ~90 min, so that four or five periods of rapid eye movement (REM) sleep with high-frequency, irregular, low-amplitude EEG patterns alternate with a similar number of slow wave sleep (SWS) stages characterized by EEG recordings showing some or predominant delta activity, a regular, high-amplitude, low-frequency pattern (CRef. 10.703). To accomplish selective deprivation, subjects are awakened whenever EEG recordings show characteristics of a certain sleep stage. Often the comparison of interest is between REM deprivation and SWS deprivation; other studies are primarily designed to ascertain the effect of REM deprivation and the control group's sleep is not specified by stage.

With more than one night's selective deprivation, it becomes increasingly difficult to prevent a selected stage of sleep, because the longer subjects are deprived of that stage, the sooner they return to it after being awakened. Extended selective deprivation, therefore, greatly reduces the ration of sleep per night as more and more awakenings are required to prevent a selected stage. Studies of selective deprivation are usually limited to one night, and some effort is made to balance the total amount of sleep loss by both groups (e.g., REM and SWS) being studied.

Selective/Partial Sleep Deprivation

Partial deprivation, accomplished by keeping subjects awake until a later hour, may have the effect of selectively depriving them of SWS because SWS is more prevalent early in a night's sleep cycle. If subjects are aroused earlier than usual in the morning, they are thought to be selectively deprived of the REM stage of sleep. However, the amount of SWS in a night's sleep can be increased by extending the hours of wakefulness preceding the night's sleep.

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While some studies indicate that reducing a sleep ration to 3 hr per night increases the amount of SWS in those hours at the expense of the REM stage, others suggest that restricting the amount of sleep per night causes SWS deprivation until the ration drops below 3 hr when REM deprivation also occurs.

Both partial and selective sleep deprivation are discussed together because they cannot be separated operationally in terms of response. Also, whereas the effects of total deprivation are relatively well established, the effects of partial and selective deprivations are often contradictory, perhaps because of the inseparability of the two. Unfortunately, studies of partial sleep deprivation usually do not consider (record) which sleep stage predominates in the partial ration.

The table summarizes the effects of partial or selective deprivation, and defines the type of sleep loss that leads to the effect.

Constraints

- Because fatigue has a circadian rhythm (with or without sleep loss), time of day is important in assessing performance deficits caused by sleep loss, but few studies report test results obtained at various times of day.

Key References

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2. Empson, J. A. C., & Clarke, P. R. F. (1970). Rapid eye movements and remembering. *Nature, 227*, 287-288.

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6. Yaroush, R., Sullivan, M. J., & Ekstrand, B. R. (1971). Effect of sleep on memory. II: Differential effect of the first and second half of the night. *Journal of Experimental Psychology, 88*, 361-366.

Cross References

10.202 Effects of different stressors on performance;

10.703 Cyclical patterns of sleep;

10.802 Sleep deprivation: effect on performance and memory;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.807 Sleep deprivation: use of physiological indicators to predict performance decrement;

10.810 Selective sleep deprivation: effect on memory;

10.811 Partial sleep deprivation: effect on vigilance and cognitive performance

10.810 Selective Sleep Deprivation: Effect on Memory

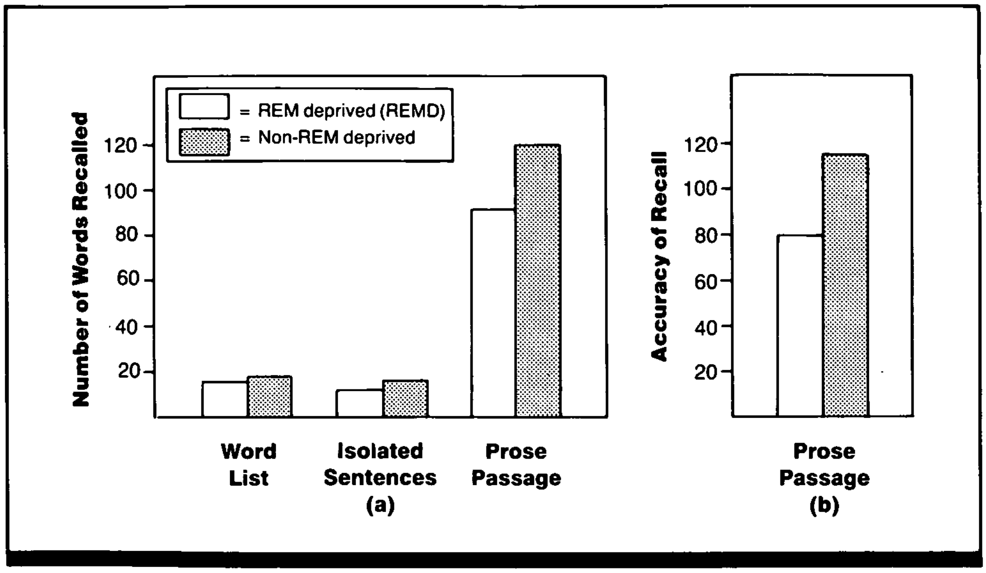

Figure 1. Number of words recalled and accuracy of recall for word list, isolated sentences, and prose passage for REM-deprived and non-REM-deprived subjects (Study 1). Accuracy of prose passage recall for REM-deprived and non-REM-deprived subjects; scale not described. (From Ref. 2)

Key Terms

Memory; rapid eye movements; sleep deprivation; sleep stages

General Description

Subjects selectively deprived of the rapid eye movement (REM) stage of the sleep cycle show impaired recall of verbal materials presented before sleep deprivation. Subjects selectively deprived of Stage 4 (S4) sleep, or of any other non-REM stage, demonstrate better delayed recall than REM-deprived (REMD) subjects. Although recall of word lists and isolated sentences is somewhat impaired in REMD subjects, the greatest impairment is shown for long coherent prose passages, including stories.

Methods

Test Conditions

- At 2100 hrs on the second of three nights spent in laboratory, loudspeaker presented taped verbal material to subjects conventionally wired for sleep recording; written recall immediately after waking at 0700 hrs
- Material to be recalled: 32 nouns (repeated 5 times), five sentences with anomalies (five repeats), and a 162-word prose passage also with anomalies (two repeats) (Study 1, Ref. 2); two stories, "The War of the Ghosts" and "The Anomalous Housewife" (two repeats) (Study 2, Ref. 3)
- Subjects paired, the REM-deprived one designated REMD, both awakened when the REMD subject entered a REM stage and kept awake 5 min (Study 1); pairs of subjects designated either REMD or S4D, each awakened upon exhibiting signs of the prohibited sleep stage and kept awake 3-4 min (Study 2)
- In Study 2, a second recall was requested after an undisturbed night's sleep (recovery from deprivation)

Experimental Procedure

- Independent variable: stage of sleep deprived (REM, S4, other non-REM stage)
- Dependent variables: number of words recalled, accuracy for prose passage and stories (means of scores given by four or five "blind" independent judges, who rated the material in a systematic way based on dividing each story into small "cognitive units")
- Subject's task: listen to oral material on previous night before sleeping and recall in writing in the morning
- 20 male undergraduate subjects (Study 1), 20 undergraduate subjects (Study 2)

Experimental Results

- REMD subjects recall fewer words from a list accurately than do subjects deprived of non-REM sleep, but the difference does not reach significance (Fig. 1a), so the result is not established.
- REMD subjects recall significantly fewer words from sentences than do subjects deprived of non-REM sleep ($p < 0.05$) (Fig. 1a).
- Compared to subjects deprived of non-REM sleep, REMD subjects recall significantly fewer words ($p < 0.02$) from an extended prose passage and have lower mean accuracy of recall scores (Fig. 1b).
- Overall recall accuracy for stories following REMD is significantly inferior to that following S4D ($p < 0.025$) (Fig. 2).
- Both REMD and S4D groups show a highly significant deterioration in recall accuracy between post-deprivation and post-recovery ($p < 0.001$) when an additional 24 hr, with one night's normal sleep, precedes delayed recall (Fig. 2).

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- The highly significant interaction between sleep deprivation group and time of recall ($p < 0.001$) indicates that recall accuracy deteriorates to a far greater extent following S4 recovery than after REM recovery.

Variability

Significance was determined by the Wilcoxon *T* test (Study 1) and analysis of variance (Study 2). Standard deviations of mean scores are given, but not analyzed in Study 1 (Ref. 2).

Repeatability/Comparison with Other Studies

Both studies reported here show comparable results (Refs. 2, 3). Other evidence that REM deprivation interferes with the consolidation in memory of verbal material has been reported (Ref. 1). Better consolidation (reduced forgetting) was found for sleep during the first part of the night when slow-wave sleep predominates than for the second part of the night when REM sleep predominates (Ref. 4).

Constraints

- Individual differences were not controlled.
- Other aspects of the sleep cycle are interrupted or altered when a single stage of sleep is prohibited.

Key References

1. Allen, S. R. (1975). REM sleep deprivation and protein synthesis inhibition: Effects on human memory. In P. Levin & W. P. Koella (Eds.), *Sleep 1974. 2nd European Congress on Sleep Research, Rome* (pp. 373-376). Basel: Karger.

*2. Empson, J. A. C., & Clarke, P. R. F. (1970). Rapid eye movements and remembering. *Nature, 227*, 287-288.

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Cross References

10.703 Cyclical patterns of sleep;

10.704 Time of day: effect on memory;

10.809 Partial deprivation of sleep: effect on performance

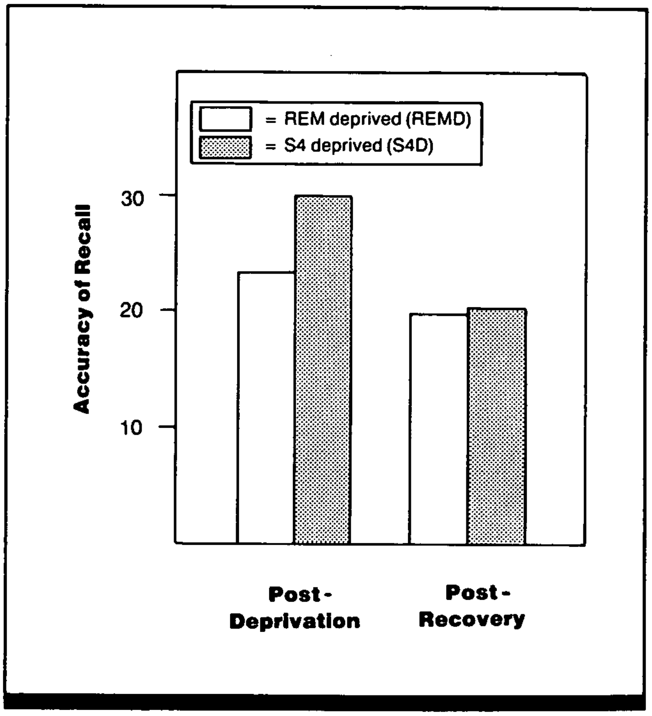

Figure 2. Mean recall accuracy for stories tested post-deprivation and post-recovery for REM-deprived and Stage 4-deprived subjects (Study 2). Scale for accuracy scores not described. (From Ref. 3)

10.811 Partial Sleep Deprivation: Effect on Vigilance and Cognitive Performance

Key Terms

Cognitive tasks; fatigue; memory; sleep deprivation; vigilance

General Description

The effects on performance of partial sleep deprivation (4 or 6 hr versus 7.5-hr of sleep) for four consecutive nights can be assessed by vigilance, calculation, and memory-span tasks. The effects of partial sleep deprivation vary with task, but generally performance decreases with less sleep. Vigilance performance is not affected by a 1.5-hr loss of sleep, but a 3.5-hr loss has a cumulative effect of reducing correct detections while preventing or reducing the visual improvement in sensitivity. Speed of performance on a self-paced calculation task is a simple function of sleep ration, showing significant cumulative effect; accuracy is not affected. On the memory-span task, however, at least until the fourth day, the smaller the sleep ration, the better the performance. This apparent reversal reflects the task requirements: passive attention on memory span compared to active processing on the others.

Methods

Test Conditions

- Sleep: rations of 7.5 (normal sleep), 6, or 4 hr per night for four consecutive nights every other week for six weeks
- Vigilance task: four 1-hr sessions per test day; 0.5-sec nonsignal tone presented at 2-sec intervals, whereas signal target was shorter tone (duration difference not given), presented randomly 40 times per hr, with 10 signals per 15 min
- Calculation task: three 1-hr sessions per test day, addition of columns of five two-digit numbers
- Memory-span (running digit) task: two 25-min sessions per test day; tape recorder presented random digits (1.5 per sec), and at random intervals (about twice a min) the sequence stopped and a bell rang, indicating subject was to write down the fourth digit which had occurred before the bell; 50 trials per session
- Each subject served for 6 wk: Weeks 2, 4, and 6 spent on leave and were with normal sleep; for 4 consecutive days of Weeks 1, 3, and 5, subject carried out tasks over 8 hr of the day with fixed sleep ration on nights preceding test days; order of presentation of sleep ration was balanced

Experimental Procedure

- Independent variable: sleep ration
- Dependent variables: for vigilance task, correct detection (hits), incorrect detections (false alarms), d' (sensitivity measure); for calculation task, speed (number of sums done), accuracy (percentage correct); for memory-span task, percentage digits correctly recalled
- Subject's task: for vigilance task, detect signal target and respond; for calculation task, add numbers, and write answer; for memory-span task, write digit occurring four digits before bell rang
- 16 subjects, enlisted men

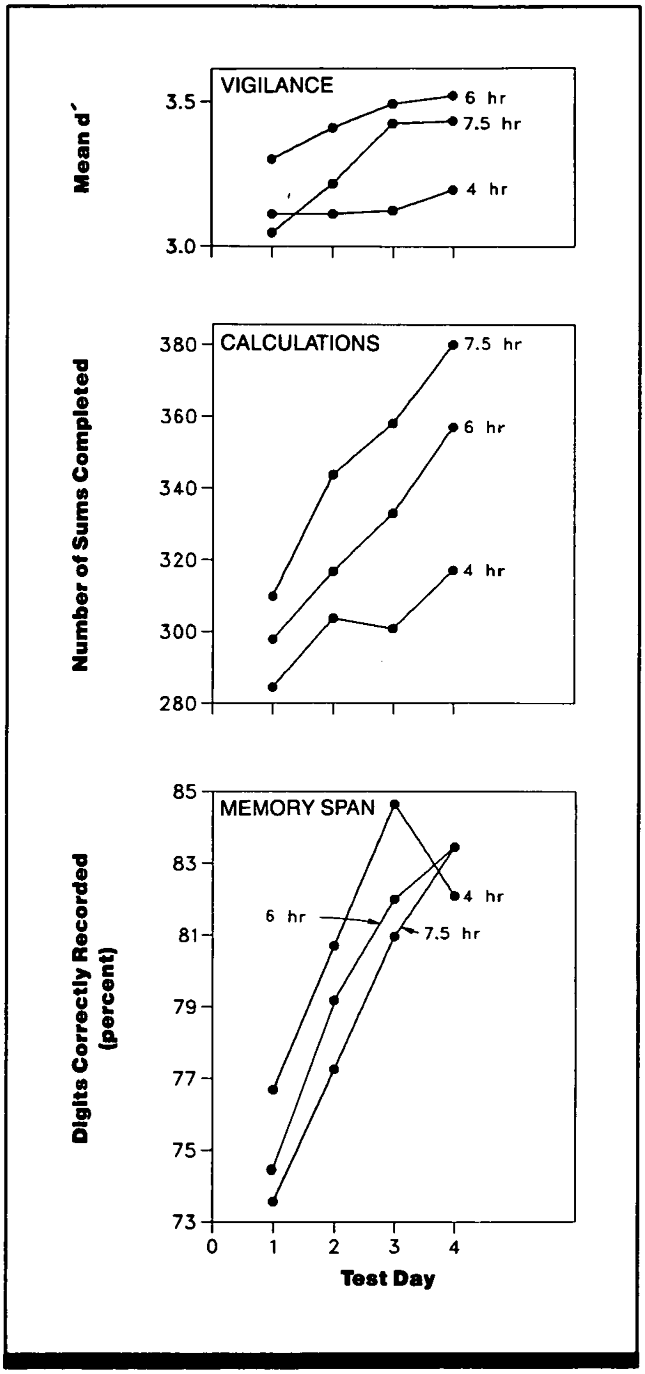

Figure 1. Performance on vigilance, calculation, and memory-span tasks as a function of test day for subjects sleeping 4, 6, or 7.5 hrs for four consecutive nights. (From Ref. 1)

Experimental Results

- On the vigilance task, number of days of sleep deprivation directly affect correct detections ($p < 0.002$).
- Percentage of correct detections increases over the 4 days for the 6- and 7.5-hr groups, but decreases for the 4-hr group. Similarly, the false alarm rate declines over the 4 days for all groups.
- The signal detection parameter d' increases over the 4 days for the 6- and 7.5-hr groups, but remains static for the 4-hr group, whose performance did not improve with repeated exposure to the task.
- On the self-paced calculation task, the amount of sleep deprivation decreases speed; the effect increases over days ($p < 0.01$).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

• On the memory-span task, amount of sleep and day of testing ($p < 0.01$) directly affect percentage of digits correctly recalled, as does the interaction of sleep with days of deprivation ($p < 0.05$).
• Superiority of sleep-deprived subjects on the memory-span task is surprising, but suggests that the task relies on passive rather than active processing of incoming digits.

Variability

Significance was determined by analysis of variance.

Repeatability/Comparison with Other Studies

Performance deficits exist after 2 days of 5-hr sleep ration per night (Ref. 2). Effects of sleep deprivation on self-paced tasks usually appear in speed rather than in accuracy measures (CRef. 10.808).

Constraints

• Individual differences in sleep requirements were neither measured nor controlled.
• Sleep deprivation was achieved by delaying onset of sleep; different results might be obtained by early awakening (CRef. 10.703).
• The statistic d' suffers from a low and variable false alarm rate.
• Scores on memory-span task were high, indicating a possible ceiling effect.

Key References

*1. Hamilton, P., Wilkinson, R. T., & Edwards, R. S. (1972). A study of four days partial sleep deprivation. In W. P. Colquhoun (Ed.), *Aspects of human efficiency: Diurnal rhythm and sleep loss* (pp. 101-113). London: English Universities Press.

2. Wilkinson, R. T., Edwards, R. S., & Haines, E. (1966). Performance following a night of reduced sleep. *Psychonomic Science*, 5, 471-472.

Cross References

10.703 Cyclical patterns of sleep;

10.805 Five-choice serial response task: effect of different stressors on performance;

10.808 Sleep deprivation: effect on circadian rhythm;

Handbook of perception and human performance, Ch. 44, Sect. 3.5

10.901 Sustained Acceleration ($+G_z$): Effect on Visual Performance

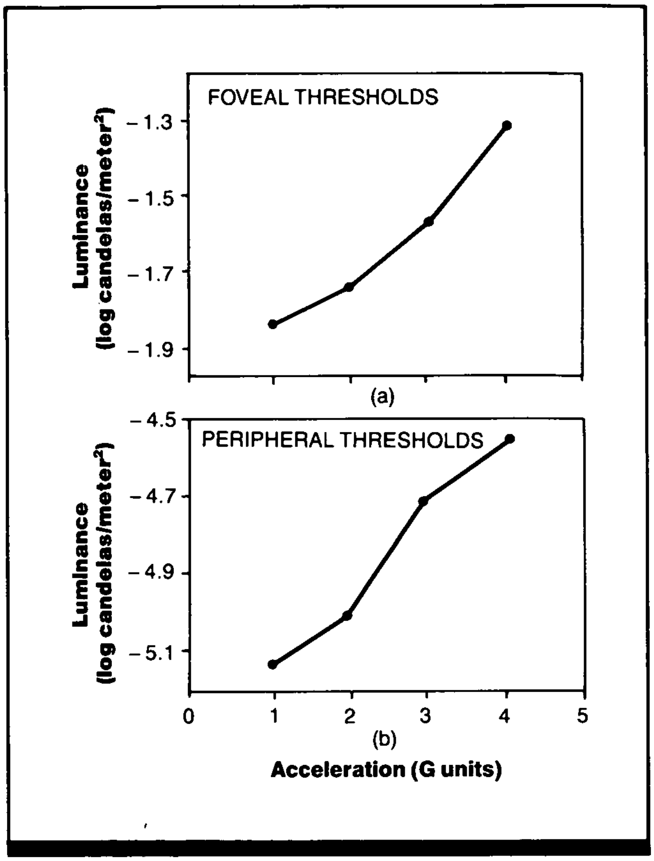

Figure 1. Threshold luminance as a function of acceleration for (a) fovea and (b) 7 deg from fixation. (From Ref. 2)

Key Terms

Field of view; G-suits; peripheral vision; sustained acceleration; target detection; visual acuity; visual sensitivity

General Description

Thresholds for both foveal (Fig. 1a) and peripheral (Fig. 1b) vision increase as positive acceleration increases from 1 to 4 G. These losses in vision are likely due to blood pressure, hence oxygen, decrease within the eyeball, and are thus ameliorated by procedures that affect that pressure, such as anti-G suits and positioning the body to make the pressure transverse (Refs. 2, 3).

Methods

Test Conditions

- Positive acceleration of 2-4 G produced using human centrifuge to simulate turning aircraft; rate of acceleration onset was 1 G every 1.5 sec; static 1-G condition served as baseline
- Foveal thresholds tested with red test patch 3 deg in diameter; peripheral thresholds with purple test patch 3 deg in diameter and 7 deg into temporal retina
- Red fixation point at center of test field
- 200-msec stimulus duration
- Light-proof, ventilated, head-size dark chanber used for stimulus presentations
- Observer was adapted 30 min for foveal measurements and 60 min for peripheral measurements; series of 1-min experimental runs followed adaptation; 2-min intervals between runs
- Thresholds recorded during transition accelerations not used

Experimental Procedure

- Threshold measured by a staircase modification of method of adjustment
- Independent variables: acceleration, retinal eccentricity
- Dependent variable: threshold luminance
- 1 subject with extensive centrifuge practice and participation in other psychophysical experiments

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

• Average thresholds in both fovea and periphery increased constantly with increasing G force (acceleration level). These thresholds are graphed in Fig. 1. All data points in each panel are significantly different from the 1-G static condition.

Variability

Complete adaptation to a particular force was defined by a variation of <0.10 log unit for five successive threshold measurements. Analysis of variance and *t*-tests were used to determine significance of the results.

Repeatability/Comparison with Other Studies

Effects on visual sensitivity at high acceleration are well known. Effects at moderate acceleration have been reported in other studies (Refs. 1, 3).

Constraints

• Peripheral determination at 7 deg eccentricity might be considered more parafoveal than peripheral.
• Sensitivity losses are likely due to blood pressure changes, which are affected by direction as well as magnitude of acceleration.

Key References

1. Howard, P., & Byford, G. H. (1956). *Threshold determination techniques on the human centrifuge* (FPRC Memo 75). Farnborough, England: Royal Air Force Institute of Aviation Medicine.

*2. White, W. J. (1960). *Variations in absolute visual thresholds during acceleration stress* (ASD-TR-60-34). Wright-Patterson Air Force Base, OH: Aeronautical Systems Division. (DTIC No. AD243612)

3. White, W. J., & Monty, R. A. (1965). Vision and unusual gravitational forces. In C. A. Baker (Ed.), *Visual capabilities in the space environment* (pp. 65-89). New York: Pergamon Press.

Cross References

10.902 Acceleration of body rotation: effect on visual acuity;

10.903 Sustained acceleration ($+G_z$): effect on contrast discrimination;

10.904 Sustained acceleration ($+G_z$): effect on target detection;

10.905 Sustained acceleration ($+G_z$): effect on dial reading errors

10.902 Acceleration of Body Rotation: Effect on Visual Acuity

Key Terms

Legibility; optokinetic nystagmus; rotary motion; spin recovery; target visibility; vestibulo-ocular reflex; visual acuity; visual-vestibular interaction

General Description

When the body is in motion, both the inner ear and the eyes send information about body stability to the brain. The **vestibulo-ocular reflex** (VOR) tends to counterrotate the movement of the eye relative to the rotation of the head. During normal head movement, this reflex serves to maintain clear vision for targets fixed with respect to the world. However, the natural and beneficial coordination of visual and vestibular system inputs can be disruptive when the head is moved violently. For example, air combat maneuvering may require reading displays (e.g., head-up displays) during maneuvers that highly stimulate the vestibular system, when there is conflicting stimulation in the peripheral visual field. This situation was simulated (Ref. 3) by rotating each observer in a chair surrounded by a non-rotating drum containing alternating vertical black and white panels (Fig. 1) while testing visual acuity. During acceleration, the visual angle required to sustain clear visual acuity doubles; the overall effect lasts for ~10 sec. During deceleration, the visual angle required to sustain clear visual acuity increases five-fold; the overall effect lasts for ~20 sec. (Fig. 2). The much larger loss of visual acuity during and immediately following deceleration is attributed to visually induced motion inputs (optokinetic inputs) that conflict with vestibular inputs.

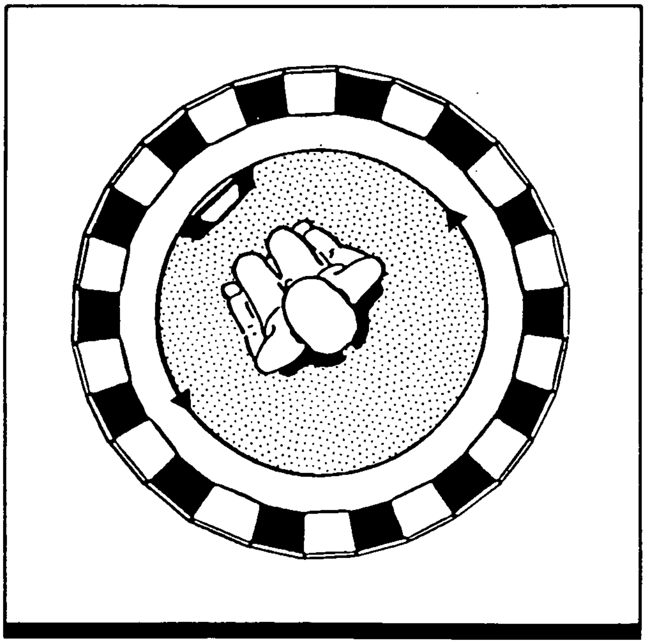

Figure 1. Top view of rotating-seat apparatus. (From Ref. 3)

The results of this study (Ref. 3) strongly suggest that minimally acceptable character size standards for routine applications may be much too small for applications that involve human rotational accelerations and decelerations.

Applications

Any condition (e.g., spin and spin recovery) that may require the reading of displayed data during and following maneuvering, when the maneuvering may involve violent body rotations.

Methods

Test Conditions

- Stille-Warner RS3 rotation device (Fig. 1); observer seated in chair at center of rotating platform; visual acuity chart 86 cm directly in front of observer and at eye level; stationary alternating black and white panels located slightly beyond acuity grid filled observer's vertical visual field; each panel subtended 13 deg horizontally; space-averaged luminance of panels 14 cd/m^2; contrast between panels 13%
- Acceleration 15 deg/sec^2 to a constant velocity of 180 deg/sec; observer rotated ~90 sec at constant velocity; deceleration rate not reported
- Acuity chart contained six rows of black stripes against white background; stripe widths and distances between stripes: Row 1, 5 min arc of visual angle; Row 2, 6 min arc; Row 3, 8 min arc; Row 4, 10 min arc; Row 5, 14 min arc; Row 6, 21 min arc; acuity chart centered on white rectangle 7.5 x 10 cm and surrounded by black square subtending 25 x 25 deg of visual angle
- Ambient illuminance not specified
- Each observer viewed all conditions; half of observers received two successive rotations in one direction followed by two successive rotations in opposite direction; remaining half rotated in opposite sequence; each trial consisted of four accelerations, rotations, and decelerations

Experimental Procedure

- Independent variables: rotational acceleration and deceleration
- Dependent variable: visual acuity (visual acuity chart row that was clearly visible)
- Observer's task: call out acuity chart row number that corresponded to the lowest-numbered row that was clearly visible
- 8 observers, Naval Flight Officer candidates who recently passed flight physical examinations; some wore corrective lenses

Experimental Results

- The visual angle needed to sustain clear visual acuity increases during both acceleration and deceleration.
- The visual angle needed to sustain clear visual acuity is significantly greater ($p < 0.001$) during deceleration than during acceleration.

Variability

Virtually identical findings resulted from two experiments (Ref. 3).

Repeatability/Comparison with Other Studies

Optokinetic stimuli in the absence of vestibular stimuli may also reduce visual acuity for targets that are fixed with reference to the head (Ref. 5).

Constraints

- A visual acuity task was used rather than an actual display reading task.
- Only one rate of acceleration and one speed of rotation were used. Different rates and speeds may produce different numerical values, but may not change overall conclusions.
- Rate of deceleration was not specified. Different deceleration rates may produce different numerical values.
- Only one background stripe width was used and different stripe widths may result in different numeric values.

Key References

1. Brandt, T., Wist, E. R., & Dichgans, J. (1975). Foreground and background in dynamic spatial orientation. *Perception & Psychophysics, 17*, 497-503.

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Cross References

1.603 Factors affecting visual acuity;

1.926 Factors affecting gain of vestibulo-ocular reflex;

10.901 Sustained acceleration (+Gz): effect on visual performance;

10.903 Sustained acceleration (+Gz): effect on contrast discrimination;

10.904 Sustained acceleration (+Gz): effect on target detection;

10.905 Sustained acceleration (+Gz): effect on dial reading errors

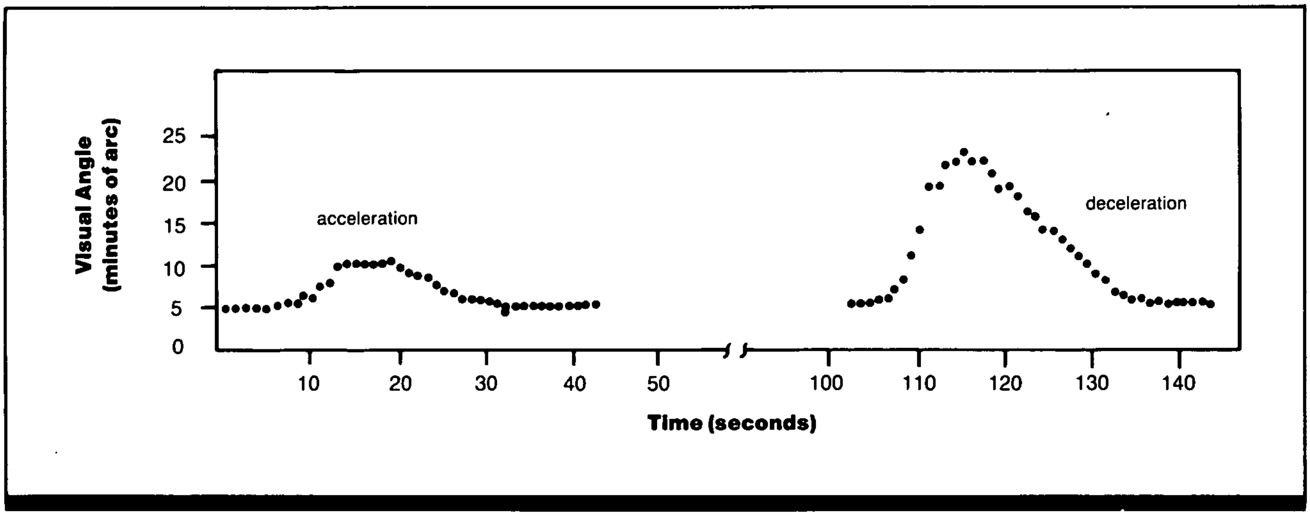

Figure 2. Angular subtense required for clear vision during rotational acceleration and deceleration. (From Ref. 3)

10.903 Sustained Acceleration ($+G_z$): Effect on Contrast Discrimination

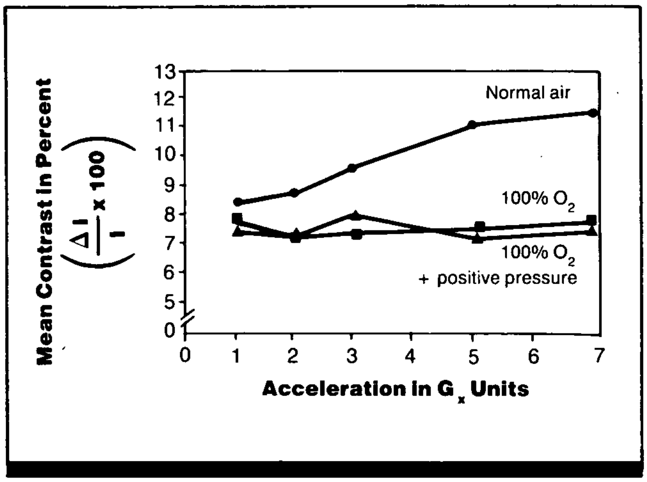

Figure 1. Mean brightness discrimination levels during G_x acceleration while observers breathed normal air, 100% oxygen, or 100% oxygen with positive pressure. (From Ref. 2)

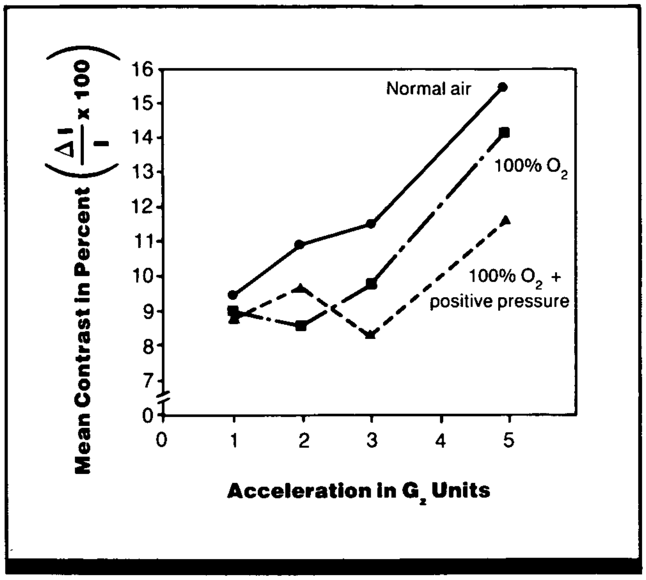

Figure 2. Mean brightness discrimination levels during G_z acceleration under the same three breathing conditions. (From Ref. 2)

Key Terms

Contrast discrimination; oxygenation; visual acuity

General Description

Both transverse (G_x) and vertical (G_z) acceleration reduce the supply of blood to the brain. Contrast sensitivity decreases with acceleration and, with prolonged transverse acceleration, breathing becomes difficult and fatiguing, chest pains develop, eyes tear, and miscellaneous discomforts may develop. With vertical acceleration, scene dimming and eventual blackout may occur; thus physiological limits for vertical acceleration are lower than those for transverse acceleration. Increasing the amount of oxygen to 100% and inhaling it under positive pressure decrease the need for increased lighting contrast. For G_x with either positive-pressure or atmospheric-pressure breathing of 100% oxygen, no increase in lighting contrast is required as it is with normal breathing of atmospheric air. At 3 G_z with pressurized 100% oxygen, less lighting contrast is required than with atmospheric breathing of either 100% oxygen or normal air.

Applications

Use of pressurized 100% oxygen to minimize loss of contrast sensitivity when exposed to high acceleration.

Methods

Test Conditions

- Observer breathed 100% oxygen at either atmospheric pressure or under positive pressure, or normal air at atmospheric pressure
- G_x (lateral) or G_z (vertical) acceleration in 15.2 m (50 ft) centrifuge: 12.5-sec upramp to peak G, 90 sec at peak G, then 12.5-sec downramp to normal
- 1, 2, 3, 5, or 7 G_x; 1, 2, 3, or 5 G_z
- 1-deg, 28-min circular spot of light produced by 500-W slide projector against 8-deg, 4-min diffuse background; opal-glass background back-illuminated to 0.03 fL with Tungsten-filament light bulbs
- Viewing distance of 44.5 cm (17.5 in.); monocular viewing through aperture

Experimental Procedure

- Method of adjustment in ascending and descending series
- Independent variables: type of acceleration, peak acceleration
- Dependent variable: threshold for detection of light spot
- Observer's task: adjust illumination until light spot was visible
- 5 medical corpsmen with extensive practice

Experimental Results

- During G_x acceleration and under the normal air breathing condition, the required brightness contrast increases as G increases. However, under conditions of 100% oxygen and pressure breathing of 100% oxygen, observers are able to maintain vision without an increase in contrast.
- During G_z acceleration, the required brightness contrast increases as G increases for all three conditions. At 3 G_z

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

and above, the condition of pressure breathing of 100% oxygen requires less contrast than breathing normal air or 100% oxygen under normal pressure.

- With 100% oxygen, breathing ease and general comfort were better with pressure breathing than with normal breathing at 5 and 7 G_x and positive 3 and 5 G_z.

Repeatability/Comparison with Other Studies

With endurance runs at 10 G_x, Watson and Chernaik (Ref. 3), using 100% oxygen with and without pressurization, found a 67% increase in endurance and easier breathing with pressurization. This supported an earlier finding of Armstrong (Ref. 1), who found easier breathing with pressurization. In the first of two experiments, Chambers et al. (Ref. 2) found that ability to perform a complex psychomotor task under high G_x and a visual luminance discrimination task under either high G_x or G_z was improved by breathing pure oxygen under pressure.

Constraints

- The background luminance was quite low (0.03 fL). At higher luminances, loss of sensitivity may be less.

Key References

1. Armstrong, R. C. (1959, January). *The effect of positive pressure breathing on transverse acceleration* (ZM-AM-001). Refer: REA 8023, Convair.

*2. Chambers, R. M., Kerr, B. S., Augerson, W. S., & Morway, D. A. (1962, July). *Effects of positive pressure breathing on performance during acceleration* (NADC-MA-6205). Johnsville, PA: Aviation Medical Acceleration Laboratory, U.S. Naval Air Development Center. (DTIC No. AD298009)

3. Watson, J. F., & Chernaik, N. S. (1961). *Effect of positive pressure breathing on the respiratory mechanics and tolerance to forward acceleration* (ASD-TR-61-358). Wright-Patterson Air Force Base, OH: Aerospace Medical Laboratory. (DTIC No. AD268565)

Cross References

10.901 Sustained acceleration (+Gz): effect on visual performance;

10.902 Acceleration of body rotation: effect on visual acuity;

10.905 Sustained acceleration (+Gz): effect on dial reading errors

10.904 Sustained Acceleration ($+G_z$): Effect on Target Detection

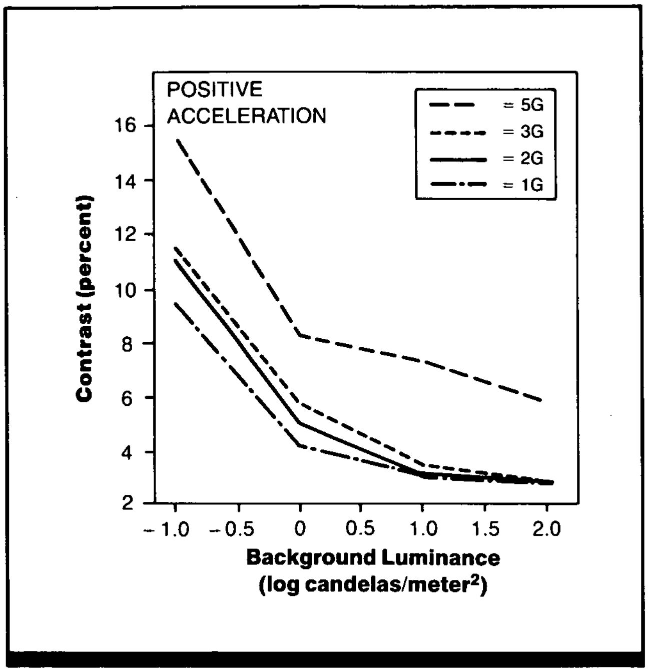

Figure 1. Threshold contrast necessary for target detection as a function of background luminance for four levels of positive acceleration. (From Ref. 1)

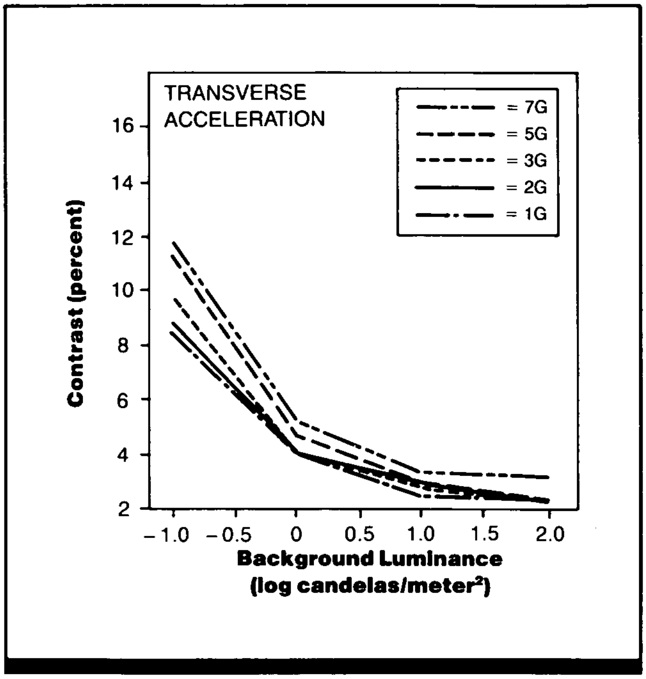

Figure 2. Threshold contrast necessary for target detection as a function of background luminance for five levels of transverse acceleration. (From Ref. 1)

Key Terms

Contrast sensitivity; sustained acceleration; target acquisition; training; visual acuity

General Description

Both positive acceleration ($+G_z$, increased force parallel to the long axis of the body and in the direction of toe-to-head) and transverse acceleration ($+G_x$, increased force perpendicular to the long axis of the body) affect the amount of contrast necessary for target detection; thresholds increase as the level of acceleration increases.

Performance is worse at high levels of positive acceleration than at high levels of transverse acceleration. Increasing target-to-background contrast or increasing overall display luminance can reduce the effects of acceleration on visual performance.

Methods

Test Conditions

- Achromatic circular background subtending visual angle of 8 deg 4 min; background luminance of 0.103, 0.994, 9.94, or 106.9 cd/m² (0.03, 0.29, 2.9, or 31.2 fL)
- Achromatic circular target subtending 1 deg 28 min produced by projector; monocular presentation
- 1, 2, 3, or 5 G positive rotation; 1, 2, 3, 5, or 7 G transverse rotation; subject wore G suit during positive acceleration runs
- Each run consisted of 12.5-sec acceleration, 90 sec at maximum G, and 12.5-sec deceleration to 1 G; subject responded during entire run

Experimental Procedure

- Method of limits
- Independent variables: type of acceleration, level of acceleration, background luminance
- Dependent variable: thresholds for target detection, defined as mean minimum detectable luminance divided by background luminance (percent contrast); thresholds based on last five ascending and last five descending responses made during the 90-sec maximum G period of run
- Subject's task: press button each time target either appeared or disappeared
- 5 subjects

Experimental Results

- Higher levels of either positive or transverse acceleration increase the amount of contrast necessary for target detection ($p<0.05$).
- The effect of acceleration is greatest for the dimmest background luminance ($p<0.05$).
- Magnitude of positive acceleration has a greater effect on target detection than does magnitude of transverse acceleration. For example, although 1-G transverse and positive acceleration require roughly the same amount of contrast (8% and 9%, respectively), 7-G transverse only requires 12%, whereas the lesser 5-G positive acceleration requires 16% ($p<0.05$).

Variability

Analysis of variance used to determine significance.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Repeatability/Comparison with Other Studies

When G force is large enough and/or gravitational stress is prolonged, peripheral vision may fade or vision may be completely lost.

Key References

*1. Braunstein, M. L., & White, W. J. (1962). The effects of acceleration on brightness discrimination. *Journal of the Optical Society of America*, *52*, 931-933.

Cross References

1.603 Factors affecting visual acuity;

1.628 Factors affecting contrast sensitivity for spatial patterns;

1.632 Contrast sensitivity: effect of luminance level (foveal vision);

10.901 Sustained acceleration ($+G_z$): effect on visual performance;

10.902 Acceleration of body rotation: effect on visual acuity;

10.903 Substained acceleration ($+G_z$): effect on contrast discrimination;

10.905 Substained acceleration ($+G_z$): effect on dial reading errors

10.905 Sustained Acceleration ($+G_z$): Effect on Dial Reading Errors

Key Terms

Reading error; sustained acceleration

General Description

Errors in reading aircraft instrument dials do not increase as acceleration increases up to 4 G under high illumination (150 cd/m^2), but as illumination decreases, reading errors typically increase with increasing acceleration for >2 G.

Applications

Situations that necessitate reading (e.g., numerical dials) during acceleration.

Methods

Test Conditions

- Panel of 12 white dials, graduated by fives or units around full circumference; five luminance levels from 0.015-150 cd/m^2 (0.004-42 mL); dials mounted on a black matte background 71 cm (28 in.) from the observer
- Acceleration conditions from 0-4 G in 1 G steps
- Free binocular viewing; 5 min of adaptation at each luminance level
- Observer wore CSU-3P anti-G suit
- Observer's oral responses recorded on audio tape recorder and later interpreted by two independent listeners

Experimental Procedure

- Independent variables: luminance of dials, degree of acceleration
- Dependent variables: number of errors in dial reading, reading time
- Observer's task: read the dial setting aloud
- 6 observers with normal uncorrected vision and extensive centrifuge experience

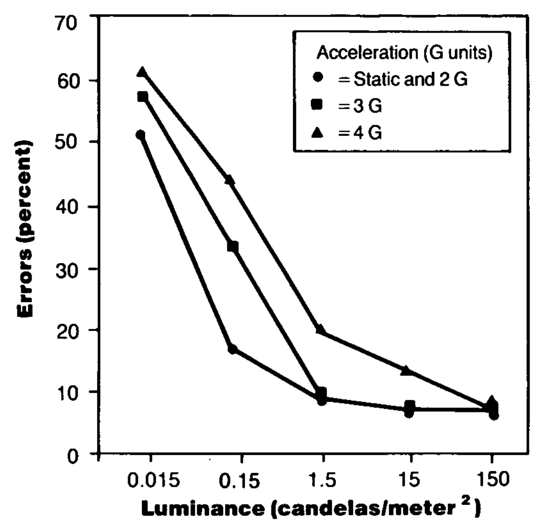

Figure 1. Number of errors in reading dial instruments as a function of luminance under different degrees of acceleration. (From Ref. 3)

Experimental Results

- Increasing illumination can compensate for loss of vision resulting from increasing acceleration.
- Increasing acceleration has no significant effect at 150 cd/m^2 luminance, and only an acceleration of 4 G has a significant effect at luminances of 15 and 1.5 cd/m^2.
- For luminances of 0.015 and 0.15, errors increase as acceleration increases to 3 and 4 G.
- Reading errors were the same for dials graduated by fives or by single units.
- The results for reading time are similar to those for errors.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

For positive G, both foveal and peripheral absolute threshold luminance for unprotected observers increase as acceleration in G units increases. The increase was ~0.1 log units for 2 G (when compared to 1 G static condition) and ~0.5 log unit for 4 G (Ref. 2).

Constraints

- Results may differ for negative or transverse acceleration.
- Only number of errors are graphed in Fig. 1; an error analysis indicated that only ~13% of the errors were ≥5 units, and these occurred primarily at the lowest luminance level.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Warrick, H. J., & Lund, D. W. (1946). *The effect of moderate positive acceleration on ability to read aircraft type instrument dials* (USAF Memorandum Report No. TSEAA 694-10). Dayton, OH: Air Materials Command, Wright-Patterson Air Force Base.

2. White, W. J. (1961). Visual performance under gravitational stress. In O. H. Gauer and G. D. Zuidema (Eds.), *Gravitational stress in aerospace medicine* (pp. 70-89). Boston, MA: Little, Brown, and Co.

*3. White, W. J., & Riley, M. B. (1958). *The effects of positive acceleration on the relation between illumination and instrument reading* (WADC-TR-58-332). Wright-Patterson Air Force Base, OH: Wright Air Development Center (DTIC No. AD206663)

Cross References

1.641 Contrast sensitivity: effect of edge sharpness;

7.108 Probability of correctly reading meters;

10.901 Sustained acceleration ($+G_z$): effect on visual performance;

10.902 Acceleration of body rotation: effect on visual acuity;

10.903 Sustained acceleration ($+G_z$): effect on contrast discrimination;

10.904 Sustained acceleration ($+G_z$): effect on target detection

10.906 Sustained Acceleration ($+G_z$): Effect on Vision and Consciousness

Key Terms

Blackout; consciousness; sustained acceleration

General Description

The maximum magnitude of acceleration ($+G_z$: headward, eyeballs down) that can be endured before symptoms develop depends on both the rate of onset of acceleration and the exposure time (Fig. 1). If the exposure time does not exceed 3 sec (solid line in Fig. 1), then tolerance probably is limited only by the body's structural strength, and a pilot can withstand very high G forces (although accelerations to only ~10 G have been tested).

If, however, positive acceleration ($+G_z$) lasts ~4-6 sec, then the average subject will experience loss of peripheral vision at ~4 G, blackout (loss of all vision) at ~4.7 G, and will become unconscious at ~5.4 G. If the acceleration lasts more than 6-7 sec, then tolerance increases by ~1.0-1.5 G (Ref. 1), because protective reflexes on the cardiovascular system come into play.

A rate of positive acceleration of 0.9 G/sec (dashed line in Fig. 1), which produces maximum acceleration of 4.5 G in 5 sec, will produce symptoms in the average subject, but a rate of acceleration of 0.45 G/sec (dotted line), which produces the same maximum acceleration in 10 sec, will not. Moreover, if the rate of onset of acceleration is 1 G/sec to a maximum of 4.7 G, the average subject will black out 3-5 sec after reaching maximum G; but if the G level is maintained beyond that time, central vision will return after ~8 sec of exposure.

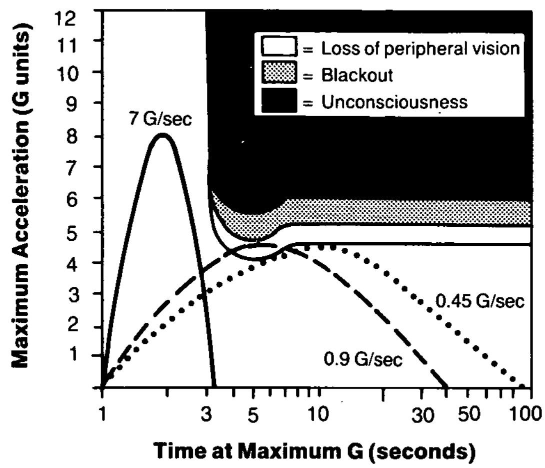

Figure 1. Rate of onset of acceleration and the exposure duration at the time of maximum G required to produce visual symptoms and unconsciousness. (From Ref. 2)

Methods

Test Conditions

- Subject seated upright in centrifuge
- Positive G force ranging from 0-10 G in 1-G steps with rate of onset of acceleration ranging from 0-8 G/sec
- Small spot of light placed centrally (foveal vision) or some distance to the side of a fixation point (peripheral vision); test conditions not standardized or specified
- Test light illuminated during centrifugal motion

Experimental Procedure

- Independent variables: rates of onset of acceleration, duration of acceleration
- Dependent variables: visibility of test light, state of consciousness
- Subject's task: operate switch to turn off light
- 1000 subjects

Experimental Results

- Average threshold for positive-G acceleration of 1 G/sec: loss of peripheral vision = 4.1 G, blackout (failure to respond to central light) = 4.7 G, and unconsciousness = 5.4 G.

Variability

Range and standard deviation of loss of peripheral vision, blackout, and unconsciousness at 1 G/sec acceleration are 2.2-7.1 G and 0.7 G, 2.7-7.8 G, and 0.8 G, 3.0-8.4 G and 0.9 G, respectively. Thus it is impossible to predict whether an individual will become unconscious or just experience a decrement in vision for a given G level.

Repeatability/Comparison with Other Studies

Over 350 references in literature (as of 1987) dealing with effects of $+G_z$. Most recent findings indicate that it takes about 14 sec to fully mobilize the cardiovascular compensatory reflex though the data cited here are still widely accepted.

Constraints

- Values and effects for negative and transverse G may differ.
- Tolerance enhanced by anti-G suits.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Gauer, O., & Henry, J. P. (1953). *Physiology of flight* (pp. 153-154, Air Force Manual 160-30). Washington, DC: U.S. Government Printing Office.

*2. White, W. J. (1961). Visual performance under gravitational stress. In O.H. Gauer & G. D. Zuidema (Eds.), *Gravitational stress in aerospace medicine* (pp. 70-89). Boston: Little, Brown & Company.

Cross References

10.901 Sustained acceleration ($+G_z$): effect on visual performance;

10.902 Acceleration of body rotation: effect on visual acuity;

10.904 Sustained acceleration ($+G_z$): effect on target detection;

10.905 Sustained acceleration ($+G_z$): effect on dial reading errors

10.1001 Techniques for Body Self-Rotation Without Surface Contact in Micro-Gravitational Environments

Key Terms

Bend and twist method; body rotation; cat reflex method; free fall; gravity; lasso method; pinwheel method; posture; reach-and-turn method; righting maneuvering; self-rotation; signal-flag method; space maneuvering; space work; touch-the-toe method; training; zero gravity

General Description

In free-space zero-gravity environments, where there is nothing to push against, changes in body orientation can be accomplished through a series of appropriate bending and twisting movements of the torso and limbs, because the total angular and linear momentums remain constant. Performing the appropriate movements in the proper sequence requires training, experience, or a provided routine. Until practice in free space makes actions largely automatic, it is useful to know some standard techniques or routines to rotate about body axes. Several routines are described that have been theoretically derived by using conservation of momentum for use in zero gravity while in earth orbit, freely falling from an aircraft, etc. Although not validated, it is likely that use of these routines will permit self-rotation. Note in figures that rotation about the relevant axis of the individual from one step to the next is not shown.

Z-Axis Rotation

The z-axis is the vertical or head-feet axis. Four z-axis rotation methods are:

1. The Cat Reflex Method. See Fig. 1a.
   (a) Start with body straight, arms straight alongside body.
   (b) Spread legs apart.
   (c) Twist upper body about the z-axis at the waist. Ignore concomitant opposite twist of legs.
   (d) Spread arms out from sides.
   (e) Draw legs together.
   (f) Untwist at waist.
   (g) Lower arms to sides.
   (h) Repeat cycle until desired rotation is attained.
2. The Bend-and-Twist Method, unlike the cat method, involves only the upper body. Throughout the procedure the legs are kept parallel to the z-axis. See Fig. 1b.
   (a) Start with body straight, arms straight alongside body, legs together and straight (position of attention).
   (b) Bend upper body to one side.
   (c) Extend arms overhead.
   (d) Rotate upper body to other side; the arms thus move from the side to the front to the other side, the back remaining nearly horizontal.
   (e) Draw arms down to parallel with torso.
   (f) Unbend body to original position.
   (g) Repeat until desired rotation is achieved.
3. The Lasso Method uses continuous motion of the arms. See Fig. 1c.
   (a) Start with body straight, arms overhead and straight.
   (b) Rotate arms continuously in same direction (clockwise or counter-clockwise) in conical motion from the shoulders until desired rotation is achieved. Keep the symmetry axis of the cones close to the body's z-axis. The required arm movements are easy, but body rotation is not quick. One or both arms may be used.
4. The Pinwheel (or Hula Hoop Movement) Method. See Fig. 1d. With body straight, hands on hips, rotate the upper body continuously in a conical fashion from the waist, bending as far backwards as forward and to the sides.

X-Axis Rotation

The x-axis is an axis passing through the torso from front to back. Three x-axis rotation methods are:

1. The Signal-Flag Method. See Fig. 1e.
   (a) With body straight, arms at sides, draw in legs to tuck position as if kneeling in prayer.
   (b) Raise one arm overhead.
   (c) Rotate raised arm from shoulder down to side.
   (d) At same time rotate other arm at shoulder outward to the side until it is overhead.
   (e) Return arms to positions in Step 2 by bending elbows and moving hands along the torso while keeping the hands and arms as close to body as possible. Repeat arm motion cycle until desired rotation is attained.
   (f) At desired rotation, straighten out legs. Many arm motions are required for one body rotation.
2. The Reach-and-Turn Method involves mainly upper body movement. See Fig. 1f.
   (a) Start as if at attention: body straight, arms to sides.
   (b) Bend upper body to the side at the waist.
   (c) Extend arms overhead.
   (d) Draw legs up to tuck position as if kneeling.
   (e) Rotate upper body at waist to other side; thus, the arms rotate from the side to overhead to the other side, while the trunk remains nearly vertical.
   (f) Pull arms down alongside torso.
   (g) Straighten legs.
   (h) Unbend body back to position of attention. All above motions must be in the sequence listed to cause rotation.
3. The Bend-and-Twist Method. See Fig. 1g.
   (a) Start with body straight, arms to sides.
   (b) Raise arms parallel to head-toe (z)-axis while tucking legs in.
   (c) Bend upper body to side at waist.
   (d) Straighten legs.
   (e) Rotate upper body at waist to other side. Thus, the arms move from the side to the front to the other side, and the back remains nearly horizontal.
   (f) Draw legs up to tuck position with arms still extended. Repeat steps above in same order.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

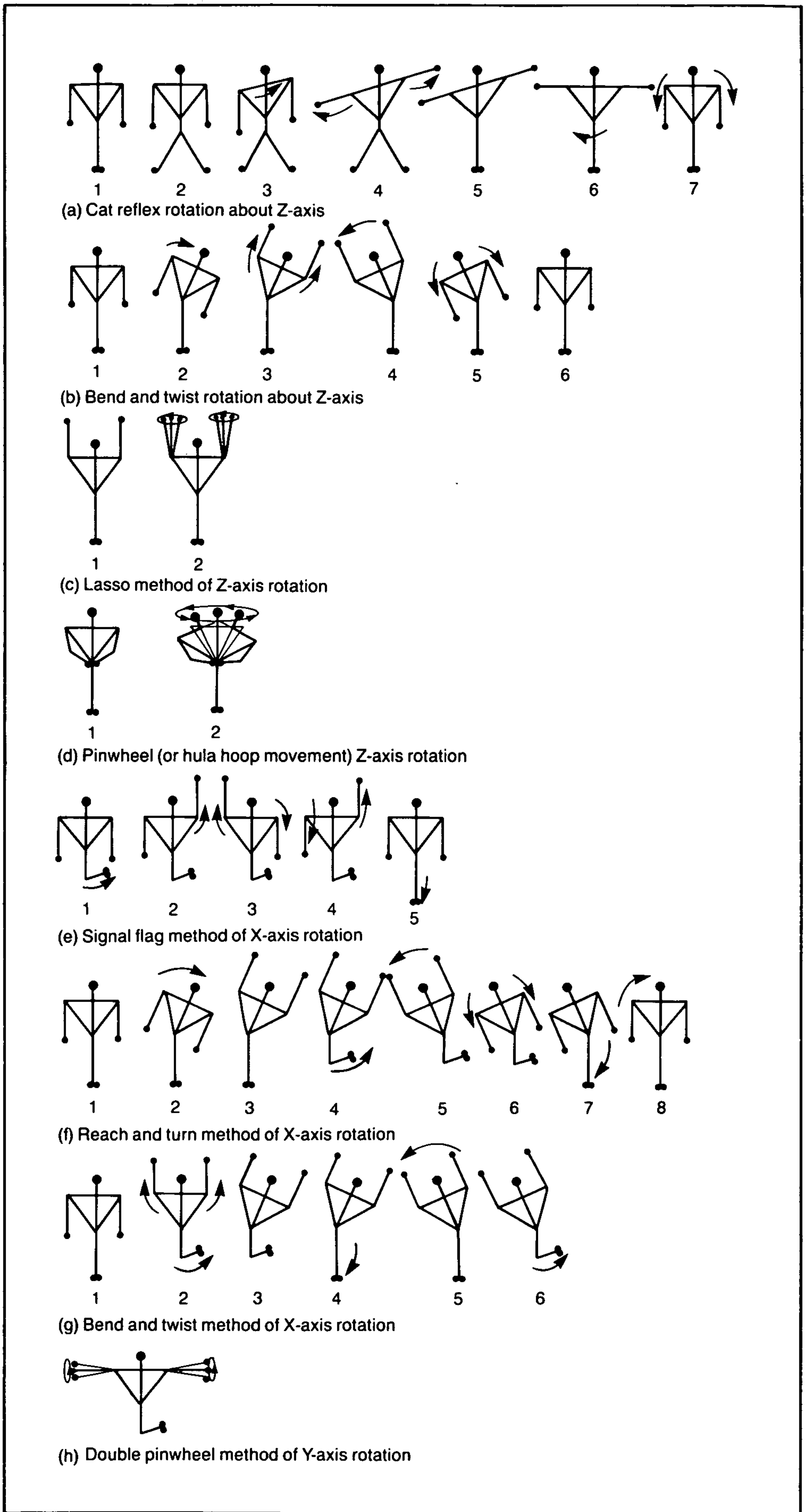

Figure 1. Routines for rotating around the z-axis (a-d), x-axis (e-g) and y-axis (h). See text for verbal description of movements.

Y-Axis Rotation

The *y*-axis is an axis passing through the torso from side to side. Two methods for *y*-axis rotation are:

1. The Double-Pinwheel Method is simple and involves continuous rotary motion, with much arm motion for a little body rotation. See Fig. 1h.
   (a) Tuck legs and feet, extend arms straight out sideways parallel to the *y*-axis.
   (b) Rotate arms in conical motion, both clockwise or both counter-clockwise.
2. The Touch-the-Toes Method involves asymmetry of limb motion, making it difficult. It also involves a high rate of energy consumption. See Fig. 2.
   (a) Body straight, arms alongside torso, legs tucked.
   (b) Straighten legs to locked position.
   (c) Bend forward at waist as if preparing to touch the toes; thus the arms slide down, remaining parallel to where they were.
   (d) Return legs to tuck position. Now in a crouched (praying) position, bend at hips, heels against buttocks, wrist at knees.
   (e) Bend backward at waist (straighten out) until upright; body straight, arms sweeping to overhead while straightening out.
   (f) Lower arms to sides. Maximum rotation is from performing all limb and trunk movements in the sagittal plane.

Key References

1. Kulwicki, P. A., Schlei, E. F., & Vergamini, P. L. (1962). Weightless man: Self-rotation techniques, (AMRL-TDR-62-129). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory. (DTIC No. AD400354)

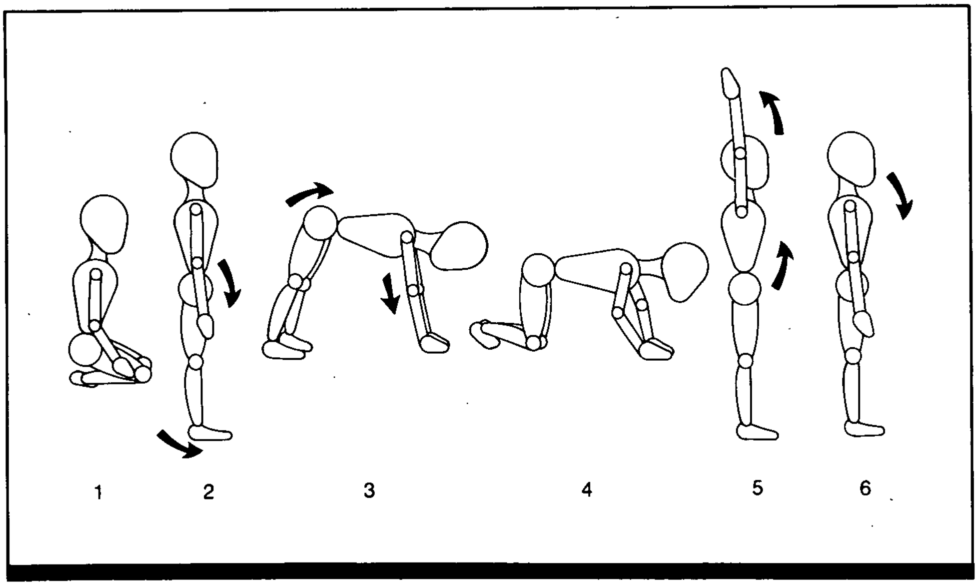

Figure 2. The touch-the-toes method of *y*-axis rotation.

Key Terms

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Glossary

Acceleration magnitude. Time rate of change of velocity, reflecting a change in either the speed or direction component of velocity.

Atlanto-occipital joint. A joint in the vertebral column at the juncture of the first cervical vertebra and the posterior part of the skull; permits flexion, extension, and lateral flexion of the head.

Basicentric axes. Axes with an origin in the contacting surface through which vibration is transmitted to the body.

Crest factor. The ratio of the frequency-weighted peak of vibration acceleration to the frequency-weighted root mean square acceleration; indicates the importance of the peak values in a motion.

Effective pilot time delay. Time delay due to processing of sensory information by the pilot.

Fatigue-decreased proficiency boundary. One of a series of boundaries defined in International Standard 2631 (1978). Exceeding this boundary for one minute is said to carry a significant risk of impaired working efficiency in many kinds of tasks, particularly those in which time-dependent effects are known to worsen performance as, for example, in vehicle driving.

Head-down display. A display located on the control panel of a cockpit or some other location that requires downward movement of the head to locate information. In contrast, a head-up display puts the most important display information where it can be seen with the head up, as on the windshield or helmet visor.

Huddleston font. A display font developed by H. F. Huddleston; based on the ASCII font, with certain arms of letters widened to make the letters more distinguishable.

Infradian. Pertaining to a rhythm with a period considerably longer than 24 hours.

SAE pad. Device of the Society of Automotive Engineers for measuring translational vibration on a seat beneath the human body.

SIT-bar. Seat interface transducer bar; device for measuring the translational or rotational vibration on a seat beneath the human body.

System dynamics. The patterns of interactions occurring in an interdependent group of components that serve a common function or form a functional unit.

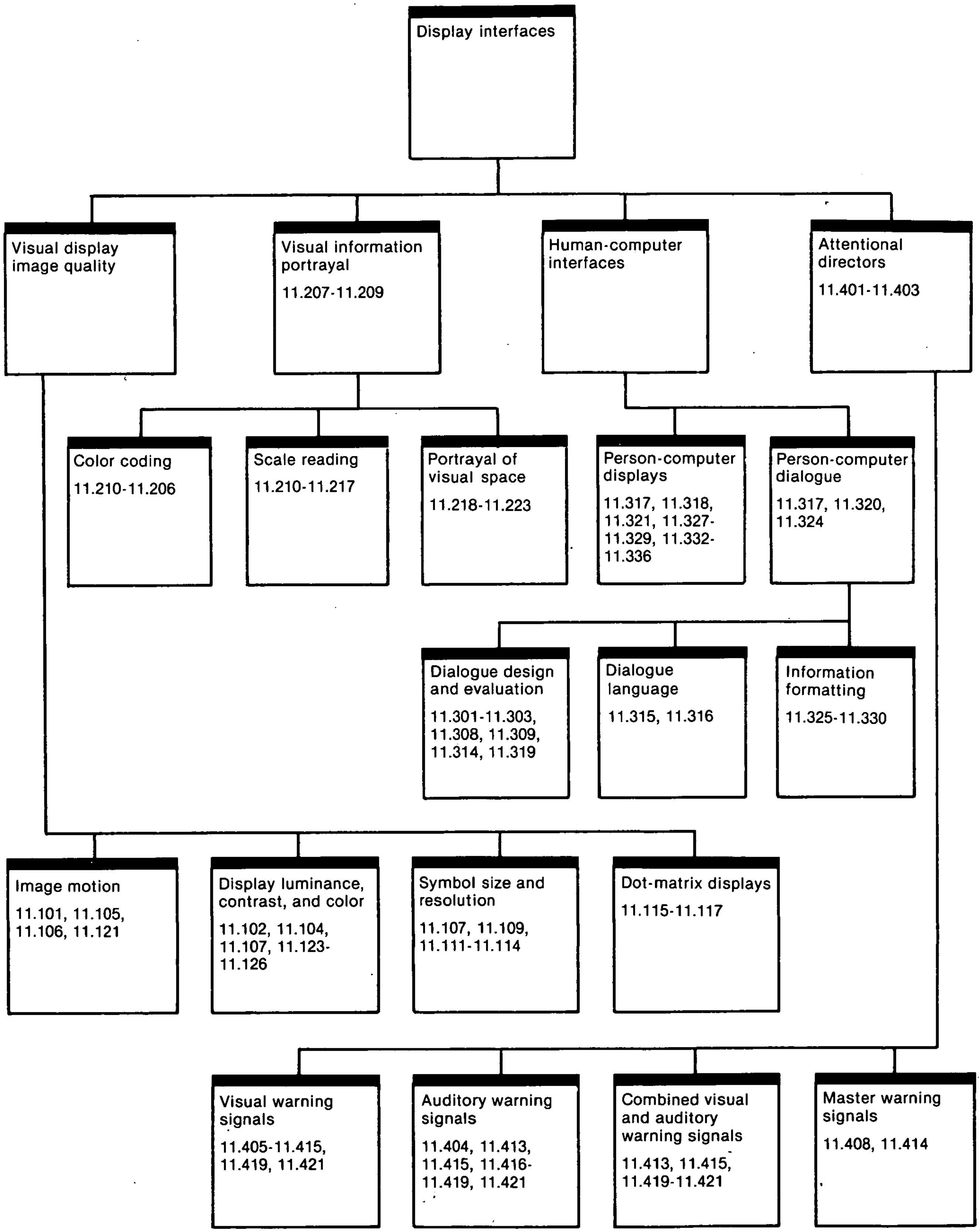
Transonic speed. Speed approximating the speed of sound in air (738 mph at sea level); often refers to speed in the range a little below to a little above the speed of sound in air, i.e., 600-900 mph.

Ultradian. Pertaining to cyclical variations with a period of less than 12 hr. (CRef. 10.709)

Vehicle dynamics. The relationship between the output of a vehicle control device and the resulting motion of the vehicle.

Vestibulo-ocular reflex. Reflexive eye movements initiated by stimulation of the vestibular system during head movements whose purpose is to stabilize the eyes with respect to the object being viewed so that the image of the object on the retina will be stationary, not be blurred by motion.

Organization of Entries



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Section 11.2 Visual Information Portrayal

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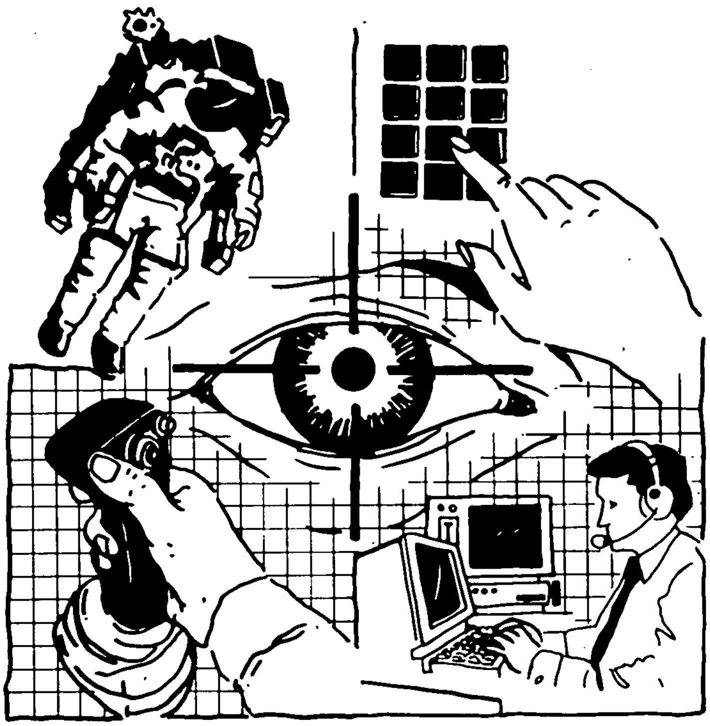
Section 11.0 Display Interfaces



11.101 Judged Image Quality on CRT Displays: Effect of Bandwidth and Image Motion

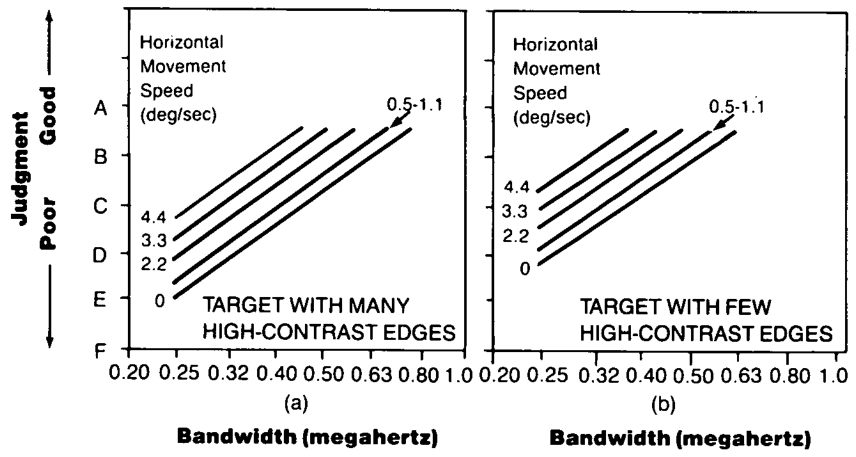


Figure 1. Relationship between bandwidth, image motion, and judged image quality for (a) targets with many high-contrast edges, and (b) targets with few high-contrast edges. (From D. J. Connor & J. E. Berrang, Resolution loss in video image, *NTC '74 Record, IEEE Publication 74*, CHO 902-F-CSCB. Copyright © 1974 IEEE. Reprinted with permission.)

Key Terms

CRT displays; display image quality; target motion; TV displays

General Description

Subjective acuity for moving images on a video (CRT) display is relatively insensitive to bandwidth reduction. The impairment in perceptibility with increased bandwidth reduction is offset by an improvement in perceptibility with increasing speed of motion across the screen. Given the same bandwidth reduction and speed of motion, impairment is greater for images with many high-contrast vertical edges than for images with only a few such edges.

Methods

Test Conditions

- Moving object traveled back and forth across field of view of TV camera; two moving scenes (standard and impaired pictures) presented on a CRT, alternating every sec for 30 sec; observer did not see object stop and change direction
- 271-TV-line system with 30-Hz frame rate; line interlace ratio of 2:1
- Observer sat 0.9 m (36 in.) from display, which had visual angle of 8 deg
- Reference (standard) scene transmitted at fixed bandwidth of 1 MHz
- Comparison (impaired) scene transmitted at bandwidths of 0.37, 0.42, 0.48, 0.56, and 0.63 MHz, keeping number of TV lines constant
- Two comparison scenes: target with high-contrast edges (set of vertical stripes) and target with low-contrast edge (a model head)
- Horizontal movement speeds of 0, ~0.5-1.1, 2.2, 3.3, 4.4 deg/sec
- Luminance values not reported

Experimental Procedure

- Method of constant stimuli
- Independent variables: edge contrast, bandwidth of comparison (impaired) scene, horizontal movement speed
- Dependent variable: judgment of image impairment on six-point scale ranging from "A" (no perceptible impairment) to "F" (extremely objectionable)
- Observer's task: to judge degree of relative impairment of comparison scene
- 4 observers, with some practice

Experimental Results

- The results plotted in Fig. 1 are approximations of the actual results. They were calculated by projecting the lines of intersections of a plane obtained by a least-squares fit and the constant-speed planes onto the zero-speed plane.
- For any given level of reduced resolution, slower moving targets show greater degradation in perceptibility than faster moving targets.
- For any given speed of movement, lower bandwidths are associated with greater impairment in perceptibility.
- Impairment in perceptibility was greater for scene with many high-contrast edges than for one with few high-contrast edges.

Repeatability/Comparison with Other Studies

Observers find unsteadiness in moving scenes less objectionable than unsteadiness in still scenes (Ref. 3)

Variability

Average standard deviation of judgments across all test conditions was ~10% of total range.

Constraints

- Many factors (such as practice, response categories, and speed of motion) can influence perceptibility of impairment of moving images and must be considered in applying these results to other conditions.

Key References

*1. Connor, D. J., & Berrang, J. E. (1974). Resolution loss in video images. *NTC '74 Record* (IEEE Pub. *74*, CHO 902-7 CSCB, pp. 54-60). San Diego, CA: Institute of Electrical and Electronics Engineers.

2. Farrell, R. J., & Booth, J. M. (1984). *Design handbook for imagery interpretation equipment.* Seattle, WA: Boeing Aerospace Co.

3. Wood, C. B. B., Sanders, J. R., & Wright, D. T. (1971). Image unsteadiness in 16 mm film for television. *Journal of the Society of Motion Picture and Television Engineers, 80*, 812-818.

Cross References

1.618 Visual acuity with target motion: effect of target velocity and orientation;

1.619 Visual acuity with target motion: effect of direction of movement and luminance level;

11.105 CRT-image motion: effect on target identification;

11.106 CRT-image motion: effect on target detection;

11.121 CRT-image unsteadiness: effect on judged picture quality

Table 1. Bandwidth reductions causing just-perceptible image degradation. (From Ref. 2, based on data of Ref. 1)

Image Motion		Bandwidth		
Degrees of Visual Angle per Second	Frame Widths per Second	Reference Scene (MHz)	Comparison Scene (MHz)	Percent Reduction (reference vs. comparison)
0	0	1.0	0.63	37
~0.5-1.1	0.23-0.45	1.0	0.56	44
2.2	0.27	1.0	0.48	52
3.3	0.41	1.0	0.42	58
4.4	0.54	1.0	0.37	63

11.102 Electro-Luminescent Displays: Minimum and Preferred Symbol Luminances

Key Terms

Display contrast; electro-luminescent displays; I.R. displays; Landolt rings; legibility; monochrome displays; radar; target recognition; TV displays

General Description

Some electro-luminescent displays are subject to washout (contrast loss) when sunlight or other bright light falls on them. To avoid washout and ensure display legibility, symbol luminance must be sufficiently greater than the luminance of the background against which the symbols are viewed. For straight-on viewing, the incremental luminance, I (or target luminance plus reflected luminance), of symbols required for correct discrimination bears an almost linear relation to display background luminance, B, when both are plotted on logarithmic axes (see Fig. 1). Thus, the incremental luminance required for legibility is an exponential function of background luminance, $I = AB^c$ where A is a constant and A and c are empirically determined. Preferred working-level luminance differences between symbols and backgrounds are considerably higher than the minimum required for correct (50%) discrimination of symbols. Methods used to fit curves to data (Fig. 1) were not reported.

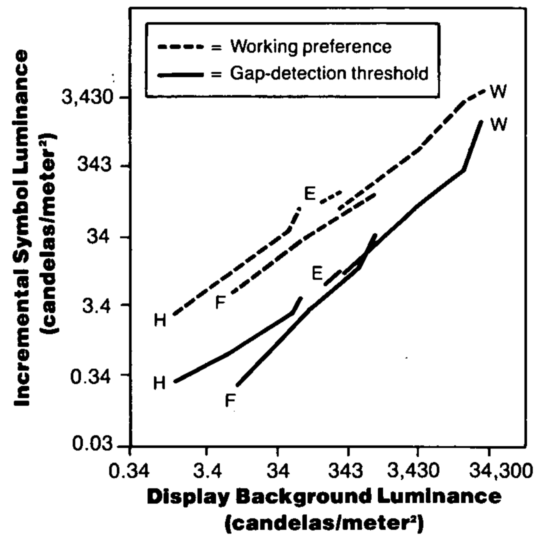


Figure 1. For four displays, W (Westinghouse), E (Electro Vision), H (Hartman), and F (Fairchild), incremental symbol luminance is plotted for both working preference and gap detection threshold as a function of display background luminance. (From Ref. 2)

Methods

Test Conditions

- One standard (Westinghouse, W) and three high-contrast (Electro Vision, E; Hartman, H; Fairchild, F) CRTs mounted in a flat black panel
- Centers of CRTs at observer's eye level; observer viewed displays at 2 angles of regard, 0 and −45 deg, from a distance of 61 cm
- Ambient illumination by two quartzite lamps (3200°K) mounted 30 and 60 deg to left of 0 deg line; ambient illuminances of 107,600, 53,800, 10,760 and 1,076 lux
- CRTs tested progressively from highest to lowest luminance in the following order: W, E, H, F
- Symbols were 4 circular rings with a diameter of 0.32 cm, 1 ring in each quadrant of display face
- A gap (60 deg segment) randomly appeared in any one of the 4 rings; position of gap in ring randomly varied
- Four trials per level per observer; threshold luminances averaged across trials and observers separately for each condition

Experimental Procedure

- Method of limits; within-subject design
- Independent variables: lamp position, observer angle of regard, ambient illuminance
- Dependent variables: gap-detection threshold, defined as lowest target luminance at which gap was correctly detected four successive times within ten responses; working-level preference, determined by having observers adjust symbol luminances to levels that would be preferred if display were part of an instrument panel
- Observer's task: locate ring containing gap while performing tracking task
- 4 observers, 25-45 years, normal vision with no color anomalies

Experimental Results

- Viewing angle has no consistent effect on performance; display glare problems at the 45-deg viewing angle are different for each CRT display.
- Based on data for the 0-deg viewing angle, no meaningful performance differences result from the four models of CRT display when equated for display background luminance, i.e., differences in reflectance characteristics of the displays tested do affect performance.
- Log of incremental luminance of symbols required for gap detection is a nearly linear function of log display background luminance over range tested and for 0-deg viewing angle, i.e., incremental luminance required, I, is approximately AB^c, where B is background luminance and A and c are determined empirically.
- Preferred working-level symbol luminances are considerably higher, but follow the same trend as the threshold data for the 0-deg viewing angle.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Threshold data agree quite favorably with comparable data for reading an electronically generated bar-graph display (Ref. 1) and with data on incremental luminance required to avoid washout of a signal on a radar scope. Preferred working-level data agree favorably with comparable comfort level data for reading an electronically generated bar-graph display (Ref. 1).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Incremental threshold luminances may be higher for accurate symbol identification than for gap detection.
- Displays used were monochrome (white or green symbology). Although the study did not examine chromatic contrast, other studies indicate that color symbols on a background of a different color may require lower incremental luminance for correct symbol identification due to the enhancement of total contrast provided by symbol-to-background chromatic contrast.
- Glare may be a confounding factor in washout, but was not systematically addressed.

Key References

1. King, R. C., Wollentin, R. W., Semple, C. A., Jr., & Gottelmann, G. (1970, August). *Electroluminescent display legibility research and development* (AFFDL-TR-70-89). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory. (DTIC No. AD878031)

*2. Knowles, W. B., & Wulfeck, J. W. (1972). Visual performance with high-contrast cathode ray tubes at high levels of ambient illumination. *Human Factors, 14*, 521-532.

Cross References

1.602 Measurement of visual acuity;

1.603 Factors affecting visual acuity;

1.606 Visual acuity: effect of illuminant wavelength;

1.618 Visual acuity with target motion: effect of target velocity and orientation;

1.624 Factors affecting detection of spatial targets;

1.644 Contrast sensitivity for Snellen letters;

12.402 Transilluminated pushbutton indicators: effects of display color and ambient illumination on reaction time

11.103 Display Surround Luminance and Subjective Visual Comfort

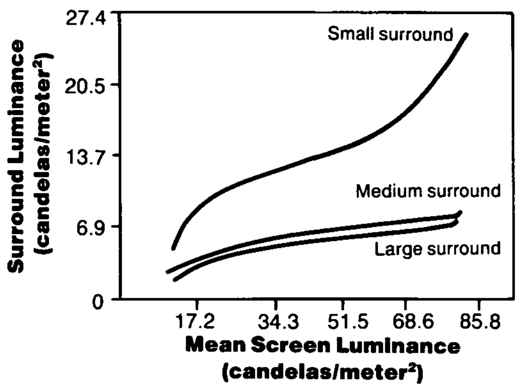


Figure 1. Mean value of surround brightness preferred by viewers of broadcast television for three surround areas at each of five screen luminances. (Adapted from Ref. 2)

Key Terms

Display brightness; display contrast; operator preference; TV displays; visual comfort

General Description

Figure 1 presents average values of preferred broadcast television surround luminance for three surround areas at each of five average screen luminances. For medium and large surrounds, visual comfort is best with surround values <8 cd/m^2. A small surround needs higher luminance to produce the greatest subjective visual comfort. An average round luminance of 8 cd/m^2 is preferred when the mean screen luminance is 17 cd/m^2. For small surrounds and a higher mean display luminance of 86 cd/m^2, an average surround luminance of 27 cd/m^2 is preferred.

Methods

Test Conditions

- Stimuli were standard 525-line broadcast video picture segments presented on a television screen; five average screen luminances (17.2, 34.3, 51.5, 68.6, or 85.8 cd/m^2); four surround luminances (6.9, 13.7, 20.6, or 27.4 cd/m^2); three surround areas (small: 12 deg vertical, 14 deg horizontal; medium: 17 deg vertical, 23 deg horizontal; large: 23 deg vertical, 32 deg horizontal)
- TV screen visual angle subtended 9 deg of visual angle vertically and 12 deg horizontally; other details not reported

Experimental Procedure

- Observers viewed all conditions of surround size, and screen and surround luminances; conditions randomly assigned; random presentation orders
- Independent variables: average screen luminance, size of surround, surround luminance
- Dependent variable: reported visual comfort
- Observer's task: state if surround luminance produced satisfactory viewing comfort
- 8 observers

Experimental Results

- Most comfortable viewing conditions are at surround luminances of <8 cd/m^2 for medium and large surrounds.
- Small surrounds produce the most comfortable viewing conditions at surround luminance of 6 cd/m^2 when average screen luminance is 17 cd/m^2. When average screen luminance is increased to 85 cd/m^2, surround luminance must increase to 26 cd/m^2 to maintain comfort.

Variability

No information on variability was given.

Constraints

- Results are limited to CRT analog displays, and may be different for reading characters or identifying symbols presented in suboptimal environments in which other displays, vibration, or washout are present.

Key References

1. Meister, D. (1984). *Human engineering data base for design and selection of cathode ray tube and other display systems* (NPRDC-TR-84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

*2. Shurtleff, D.A., Botha, B., & Young, M. (1966, May). *Studies of display symbol legibility: IV. The effect of brightness, letter spacing, symbol-background relation and surround brightness on the legibility of capital letters* (ESD-TR-65-134). Bedford, MA: Hanscom Air Force Base, Electronic Systems Division. (DTIC No. AD633853)

Cross References

11.102 Electro-luminescent displays: minimum and preferred symbol luminances;

11.112 CRT symbol size and stroke width: effect on legibility;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

12.402 Transilluminated pushbutton indicators: effects of display color and ambient illumination on reaction time

11.104 Recognition of Vehicular Targets on CRT Displays

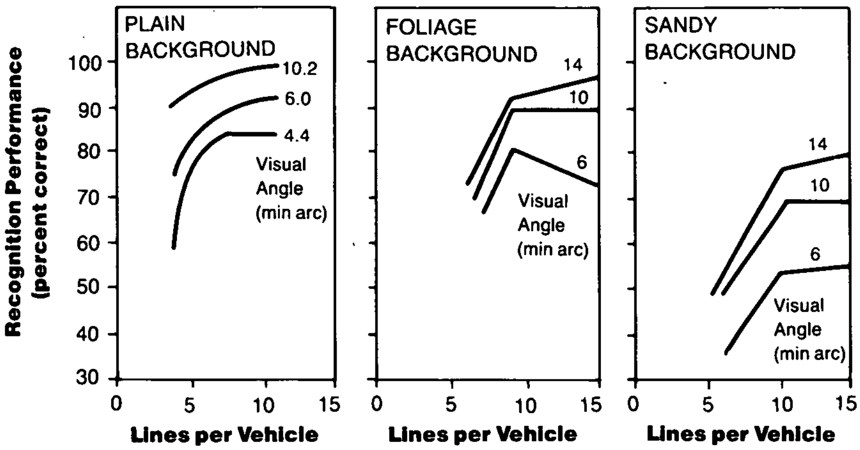


Figure 1. Recognition of vehicles displayed on a CRT as a function of number of scan lines and visual angle subtended for plain, foliage, and sandy backgrounds. (From Ref. 1)

Key Terms

CRT displays; radar; reconnaissance; scan lines; target acquisition; target recognition

General Description

Recognition of vehicles displayed on a CRT improves with an increasing number of scan lines and larger visual angle of the image. When comparing performance according to plain, foliage, and sandy backgrounds, recognition is best with a plain background and worst with a sandy background; however, test conditions are not identical for the three types of background.

Methods

Test Conditions

- Photographs of scale models of nine types of military vehicles presented on 525-line, 2:1 interlaced closed-circuit TV with bandwidth of 10 Hz to 10 MHz and signal-to-noise ratio >30 dB, ambient illumination on monitor face <32.28 lux (3 fc); display size 16.51 × 12.19 cm
- Plain background condition: side views of vehicles; 3.7, 7.0, 10.8 scan lines per vehicle, visual angles of 4.4, 6.0, 10.2 min arc of visual angle; highlight luminance 62 cd/m²
- Foliage and sandy backgrounds: views 60 deg oblique from nadir; 6, 10, 15 scan lines per vehicle; visual angle of 6, 10, 14 min arc; highlight luminance 137 cd/m²
- For all conditions, scan lines per vehicle varied by changing distance from TV camera to photograph, which also changed scale; visual angle subtended changed by changing viewing distance to display

Experimental Procedure

- Method of constant stimuli
- Independent variables: number of scan lines per vehicle, size of visual angle subtended by vehicular target, type of background
- Dependent variable: percent correct identification of vehicular target
- Observer's task: identify vehicle from among nine possible alternatives; no feedback provided
- 9 observers with extensive practice

Experimental Results

- Identification performance is better for greater number of scan lines per vehicle and larger visual angles.
- Performance improves sharply as number of scan lines (per target) increases from 3.7-6 to 7-10 and then generally levels off.
- Performance improves as the visual angle subtended by the targets increases. For foliage and sandy backgrounds, greatest improvement is seen when size is increased from 6 to 10.2 min arc of visual angle; there is less improvement with a further increase to 14 min arc.
- Performance is best for plain background followed by foliage background, and worst for sandy background. The sandy background probably gives less feature interference than foliage, but has the same luminance as vehicular highlights.

Variability

No information on variability was given.

Constraints

- Many factors, such as target shape and size, practice effects, luminance, and adaptation conditions can influence vehicular identification and must be considered when applying these results to other viewing conditions.
- Test conditions for plain background differ from those for foliage and sandy backgrounds; the plain background was used in one experiment and the foliage and sandy backgrounds were used in another experiment.

Key References

*1. Erickson, R. A., & Hemingway, J. C. (1970, September). *Image identification on television* (NWC-TP-5025). China Lake, CA: Naval Weapons Center. (DTIC No. AD876331)

Cross References

1.618 Visual acuity with target motion: effect of target velocity and orientation;

1.625 Target detection: effect of target spatial dimensions;

1.634 Contrast sensitivity: effect of target orientation;

1.643 Contrast sensitivity: effect of target shape and illumination level;

1.652 Orientation-selective effects on contrast sensitivity;

7.517 Search time: effect of number of background characters and display density;

7.525 Target acquisition in real-world scenes;

11.105 CRT-image motion: effect on target identification;

11.107 Visual simulation of aircraft silhouettes: contrast and resolution requirements

11.105 CRT-Image Motion: Effect on Target Identification

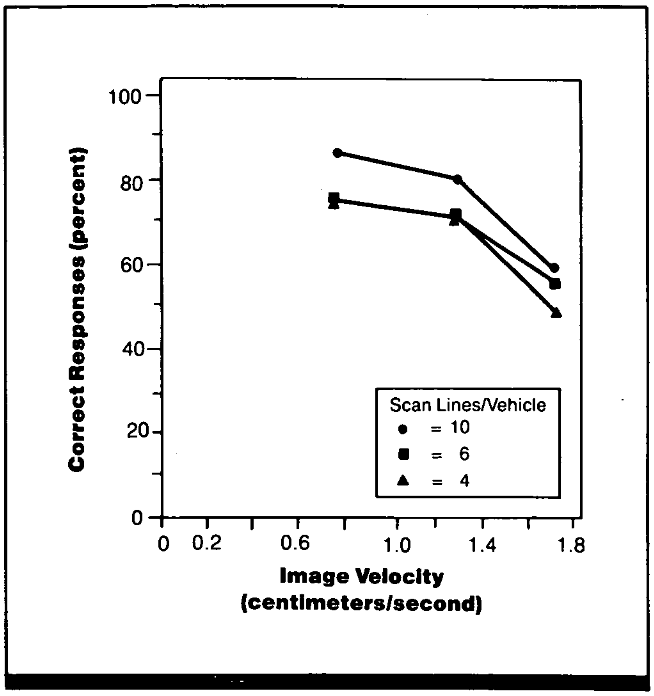


Figure 1. The probability of correct identification of a moving form on a CRT as a function of image velocity and number of scan lines per form. (From Ref. 1)

Key Terms

CRT displays; radar; scan lines; target acquisition; target identification; target motion; visual simulation

General Description

Identification of moving vehicular forms on a CRT is adversely affected by increasing image velocity and decreasing number of scan lines per form.

Methods

Test Conditions

- Vehicular form moving left to right across 525-TV-line system with bandwidth of 10 MHz and signal-to-noise ratio >30 dB; ambient illumination on vidicon faceplate of 32 lux (3 fc); P4 phosphor
- Viewing distance 60.96 cm; display size 13.46 cm square
- 4.0, 6.0, or 10.0 scan lines per form
- Image velocity of 0.76, 1.22, 1.68 cm/sec; image movement across scan lines
- Five forms consisted of three different vehicles and two forms resembling vehicles; one presentation every 5 sec
- > six trials per observer per data point

Experimental Procedure

- Method of constant stimuli; feedback conditions not reported
- Repeated measures design
- Independent variables: type of form, image velocity, number of scan lines per form
- Dependent variable: percent correct identification of vehicular form
- Observer's task: identify form at each presentation
- 12 highly practiced observers

Experimental Results

- Percent correct identification of vehicular forms in a CRT display declines as image velocity increases (and hence exposure time decreases).
- Percent correct identification decreases as the number of scan lines per form decreases.

Variability

No information on variability was given.

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Many factors, such as target size and shape, luminance, and exposure duration can influence form identification and must be considered in applying these results to other viewing conditions.

Key References

*1. Erickson, R. A., Hemingway, J. C., Craig, G. L., & Wagner, D. W. (1974, February). *Resolution of moving imagery on television: Experiment and application* (NWC-TP-5619). China Lake, CA: Naval Weapons Center. (DTIC No. ADA918949)

Cross References

1.618 Visual acuity with target motion: effect of target velocity and orientation;

1.620 Visual acuity with target motion: effect of direction of movement and target orientation;

11.104 Recognition of vehicular targets on CRT displays

11.106 CRT-Image Motion: Effect on Target Detection Performance

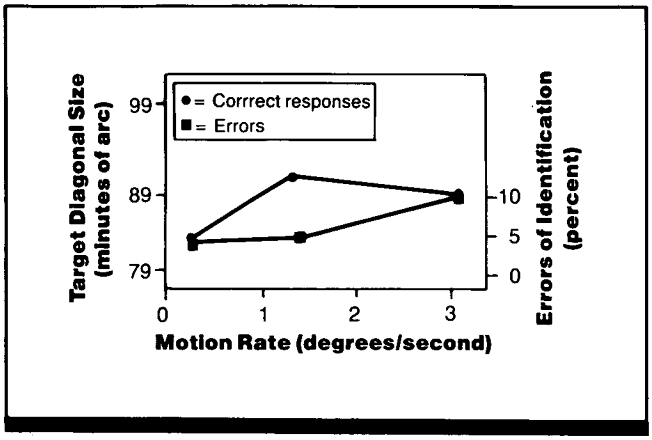


Figure 1. Target size when identified and errors in identification at different rates of target motion. (From Ref. 1)

Key Terms

CRT displays; CRT image motion; identification; reconnaissance; target acquisition; target detection; target motion

General Description

The target size required for identification increases only slightly as image motion increases in a CRT display, but the likelihood of error more than doubles.

Applications

CRT displays in which moving targets must be detected and identified.

Methods

Test Conditions

- High-resolution air-reconnaissance transparencies and videotapes displayed on a CRT to simulate a diving attack; one target (of 32) per trial (attack)
- Two Sony model 120A 3.5 MHz video tape recorders used to play back target attacks
- Four types of CRT used to display diving attacks: Degraded Conrac CNB8, Conrac CNB8, Shibaden, Sony
- Average target motion rates of 0.25, 1.33, or 3.25 deg/sec simulated conditions of no, low, or high turbulence (slight movement of target even for "no movement" condition)
- Initial apparent altitude ranged from 2438.4 to 14, 020.8 m (8,000 to 46,000 ft) and ended at 243.8 to 1402.1 m (800 to 4,600 ft)
- Changes in CRT displays corresponded to aircraft speeds of 150-900 knots; attack durations from 20-140 sec (mean = 69 sec); dive angle from 10-60 deg
- Observer saw marked target for 30 sec before attack on one of six briefing photographs; photograph remained displayed at 45-deg angle below CRT display during attack
- Ambient illumination 538 lux (50 fc); surround-to-display brightness ratios within range that did not affect performance

Experimental Procedure

- Balanced-for-residual-effects Latin square design
- Independent variables: display size, target size, target motion-rate, display degradation
- Dependent variables: target size (in min arc of visual angle) at time of correct identification, accuracy of identification
- Observer's task: identify and place tracking gate on CRT target that had been marked on briefing photograph
- 16 observers with 20/15 or better uncorrected near binocular visual acuity

Experimental Results

- Target size required for identification increases as target motion increases from 0.25-1.33 deg/sec and then declines slightly.
- Errors in identification rise only slightly as target motion increases to 1.33 deg/sec but double with a further increase to 3.25 deg/sec.

Variability

Individual threshold sizes were within ± 12% of the group mean.

Constraints

- Photographs were made under conditions of extremely good visibility. Meteorological haze may affect the results.
- Experience of the observers was not specified.

Key References

*1. Bruns, R. A., Wherry, R. J., Jr., & Bittner, A. C. (1970). *Dynamic target identification on television as a function of display size, viewing distance, and target motion rate* (NMC-TP-70-60). Point Mugu, CA: Naval Missile Center. (DTIC No. AD877006)

Cross References

1.620 Visual acuity with target motion: effect of direction of movement and target orientation;

5.607 Factors affecting target localization;

7.520 Controlled and automatic visual search;

7.522 Visual search for moving and static targets;

7.526 Detection of objects and events in real-world scenes;

7.611 Prediction of aircraft detectability;

7.613 Effect of alerted and unalerted search on target acquisition;

11.101 Judged image quality on CRT displays: effect of bandwidth and image motion;

11.105 CRT-image motion: effect on target identification;

11.121 CRT-image unsteadiness: effect on judged picture quality

11.107 Visual Simulation of Aircraft Silhouettes: Contrast and Resolution Requirements

Table 1. Mean distance (kilometers) for aspect recognition of TA-4J aircraft silhouettes for 36 combinations of target and background luminance and projector resolution. (Adapted from Ref. 3)

Target Luminance (cd/m^2)	Background Luminance (cd/m^2) 0.44	0.88	2.00	Background Luminance (cd/m^2) 0.44	0.88	2.00
	1.0 min arc of visual angle per line pair			1.3 min arc per line pair		
0.96	3.7			3.4		
2.00	4.5	3.9		4.2	3.7	
6.03	5.3	4.4	4.0	4.6	4.7	3.9
12.16	5.4	5.5	5.1	5.4	5.4	5.0
	1.6 min arc per line pair			1.9 min arc per line pair		
0.96	3.1			3.0		
2.00	3.7	3.4		3.5	3.2	
6.03	4.1	4.6	3.4	4.0	4.2	3.4
12.16	4.4	4.7	4.4	4.4	4.0	4.0

Key Terms

Air combat maneuvering; aircraft simulators; contrast sensitivity; simulation; spatial resolution; target acquisition; target aircraft orientation; target recognition; training; visual simulation

General Description

Aspect recognition distance is the distance at which observers can determine whether silhouettes of simulated aircraft are diving or climbing. Aspect recognition involves cues of size and shape. The effects of contrast, resolution, and luminance were examined in a visual flight simulator; target aircraft aspect identification is better with target-to-background luminance contrast of approximately 25:1 than with lower contrast (see Table 1). Performance is also better with high target resolution. Aspect identification performance at the highest contrast condition is 50-100% better than at the lowest contrast, while the highest resolution yields only approximately 20% better performance than the lowest. In three conditions with the same target-to-background contrast, higher background luminances result in slightly better performance.

Applications

Designing dynamic simulators of military aircraft for training or in which to evaluate air combat maneuvering performance using alternative displays, controls, or tactics.

Methods

Test Conditions

- Targets were achromatic (bluish-white) computer-generated images of a TA-4J aircraft, length of 10.7 m, wingspan of 8.2 m
- 16 stationary aircraft orientations with the same length/width ratio; four views of the aircraft, representing four rotational positions relative to observer's line of sight, at various simulated distances
- Stimuli displayed in a flight simulator; zoom optics system varied field-of-view of projected aircraft; resolution varied by manipulating field-of-view of the target projector; viewing distance 2.8 m
- >100 measurements per observer per combination of variables tested

Experimental Procedure

- Staircase method; within-subject partial factorial design
- Independent variables: display resolution, display background luminance, target luminance (see Table 1)
- Dependent variable: target aircraft aspect threshold, defined as 0.67 probability of correct aspect identification
- Observer's task: identify aspect (climbing or diving) of simulated target aircraft
- 4 observers, all screened for dynamic and static contrast sensitivity

Experimental Results

- All main effects are significant.
- Over the ranges studied, target-to-background luminance contrast accounts for the most variance, and background luminance the least.
- Resolution has the most persistently significant main effect.
- In the best experimental condition (resolution 1.0 min arc of visual angle per TV line pair, target luminance 12.16 cd/m^2, and background luminance 0.44 cd/m^2), average aspect recognition thresholds occur at >8.4 km (4 miles) (a 5.9-min arc target). In the most degraded condition (1.9-min arc per TV line pair, target luminance 0.96 cd/m^2, and background luminance 0.44 cd/m^2), average thresholds occurred at approximately 2.5 km (a 10.6-min arc target).
- A multiple regression analysis was performed to develop an equation to predict target aspect recognition distance thresholds based on log background luminance, log contrast, and numbers of lines of resolution. The following equation describes the relationship:

Retinal size of target silhouette in min arc = + 0.52 (background luminance in cd/m^2) − 2.02 (resolution in min arc per line pair) − 0.30 (target luminance in cd/m^2) + 12.08

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The main effects of the study reported here were replicated in a subsequent study (Ref. 3). The findings agree with the literature on spatial vision (Ref. 2) and are in accord with television legibility studies (Ref. 5). In a subsequent study (Ref. 3), direction of view (to the side versus straight ahead) had no effect on performance. However, silhouettes of approaching/retreating aircraft could only be identified at considerably closer ranges.

Constraints

- The data contained here apply only to silhouettes of climbing/diving aircraft, and not to aircraft that are approaching or retreating.
- The results may not apply to silhouettes of different aircraft types.
- The data presented here apply only to non-moving targets.
- Only one limited set of 16 targets orientations was used.
- Only 4 observers were used in the study.
- Only targets against darker backgrounds were investigated.

Key References

1. Ginsburg, A. P., Evans, D. W., Sekuler, R., & Harp, S. A. (1982). Contrast sensitivity predicts pilots' performance in aircraft simulators. *American Journal of Optometry and Physiological Optics, 59*, 105-109.

2. Graham, C. H. (Ed.). (1965). *Vision and visual perception.* New York: Wiley.

*3. Kennedy, R. S., Berbaum, K. S., Collyer, S. C., May, J. G., & Dunlap, W. P. (1984, December). *Visual simulation requirements for aircraft aspect recognition at real world distances* (NAVTRAEQUIPCEN-81-C-0105-5). Orlando, FL: Naval Training Equipment Center. (DTIC No. ADA151040)

4. Lamar, E. S., Hecht, S., Shlaer, S., & Hendley, C. D. (1947). Size, shape and contrast in detection of targets by daylight vision. I. Data and analytic description. *Journal of the Optical Society of America, 37*, 577-599.

5. Shurtleff, D. A. (1967, January/February). Studies in television legibility — A review of the literature. *Information Display, 1*, 40-45.

Cross References

1.618 Visual acuity with target motion: effect of target velocity and orientation;

1.625 Target detection: effect of target spatial dimensions;

1.634 Contrast sensitivity: effect of target orientation;

1.643 Contrast sensitivity: effect of target shape and illumination level;

1.652 Orientation-selective effects on contrast sensitivity;

7.525 Target acquisition in real-world scenes;

11.104 Recognition of vehicular targets on CRT displays

11.108 Television Display Resolution: Effect on Time and Accuracy for Symbol Identification

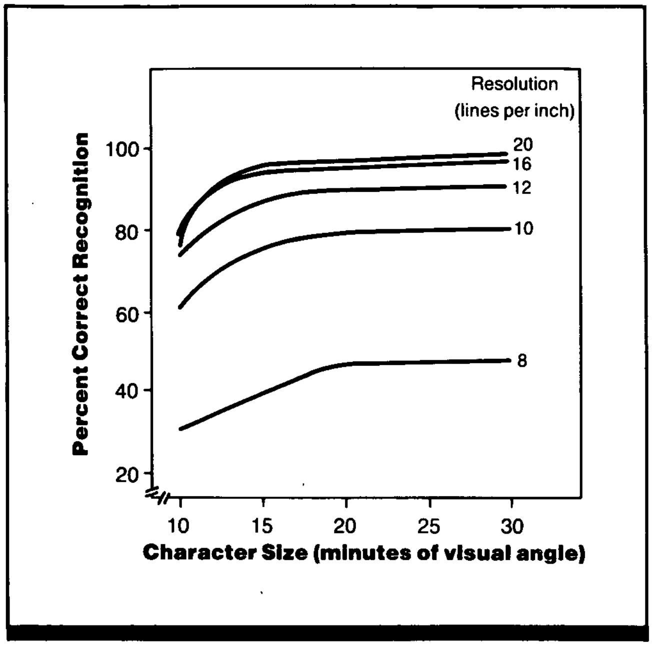


Figure 1. Alphanumeric character recognition accuracy as a function of character size and vertical resolution. (From C. H. Baker & R. Nicholson, *Raster scan parameters and target identification*, Proceedings of the 19th Annual National Aerospace Electronics Conference. Copyright © 1967 IEEE. Reprinted with permission.)

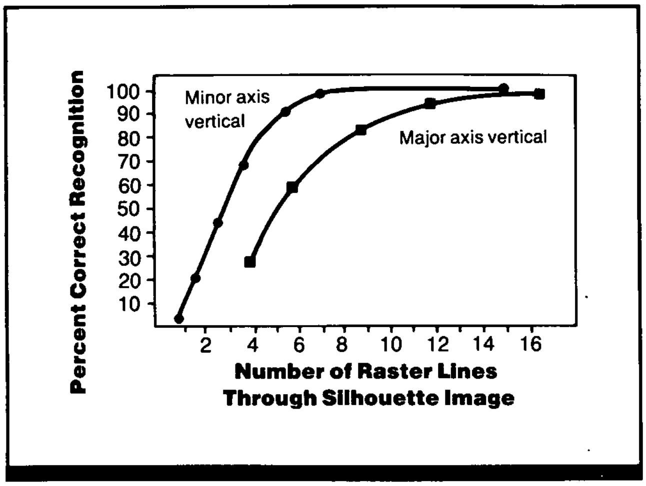


Figure 2. Symbol recognition accuracy as a function of orientation and vertical resolution. (From C. H. Baker & R. Nicholson, *Raster scan parameters and target identification*, Proceedings of the 19th Annual National Aerospace Electronics Conference. Copyright 1967 © IEEE. Reprinted with permission.)

Key Terms

Alphanumeric displays; character recognition; CRT displays; information display; Landolt rings; legibility; monochrome displays; vertical resolution; visual acuity

General Description

For high accuracy in alphanumeric character recognition, minimum vertical symbol resolution is 12 television lines per symbol height (Fig. 1). Character recognition improves as character size increases from 10-20 min arc of visual angle. Correct recognition of silhouette images of familiar objects improves as vertical resolution increases to seven lines per symbol height when the smaller dimension of the silhouette is vertical. When the major axis of the image is displayed vertically, recognition accuracy improves as vertical resolution increases to 16 lines per symbol height (Fig. 2).

Applications

Monochrome, raster-scanned television displays used for alphanumeric information display in nonvibrating, normal gravity environments.

Methods

Test Conditions

- Three different types of stimuli used: alphanumeric characters, Landolt "C" visual acuity forms, and silhouettes of familiar objects
- Alphanumeric characters had stroke widths of 0.16 cm; character heights: 10, 15, 20, and 30 min arc; height-to-width ratios of 1:1, 1.5:1, 2:1; 20 characters used: A, B, C, E, F, G, H, J, K, L, M, O, P, R, U, W, X, 4, 8, 9; resolution was 8, 10, 12, 16, or 20 raster lines per in.
- Landolt "C" stimuli presented with an overall stroke width of 0.76 cm; height of an annulus was five times the stroke width of the annulus, and the gap in the annulus was equal to the stroke width; size: 5, 7, 10, and 20 min arc, resolution was 10, 13, 16, or 23 raster lines per in. corresponding to 3, 4, 5, or 7 lines per symbol
- Silhouette stimuli ranged from 1.15:1 to 7.5:1 major-to-minor dimension ratios; objects included aircraft, handgun, horse, cup, brush, tank, man, weapons, automobile, wrench, missile, and fork; silhouettes were presented horizontally and vertically; silhouettes' major dimension 20 or 30 min arc, one-half in. on screen; resolution was 8, 12, 18, 24, 33, or 66 raster lines per in.

• All stimulus images generated from 35-mm film transparencies and displayed on a raster-scanned, 43-cm video monitor with P-4 phosphor; active scan line-to-inactive space ratio 1:1; stimuli presented with negative contrast (dark images in light background); background luminance not specified

• Viewing distances: Experiment 1: 131, 262, 381 and 542 cm; Experiment 2: 145, 218, 289, and 436 cm; Experiment 3: 145 and 218 cm

• Each observer viewed eight images at four distances, four resolutions, and three raster scan ratios; each observer viewed only one category of stimulus

• Stimuli presented one at a time

Experimental Procedure

• Between-subjects factorial design

• Independent variables: viewing distance resolution: raster lines per symbol height or per in.

• Dependent variables: accuracy of symbol identification (percent correct), response time

• Observer's task: verbally identify each stimulus character or silhouette as quickly and accurately as possible. In the Landolt "C" identification conditions, identify orientation of gap in ring

• 24 observers

Experimental Results

• Observers make more accurate identifications with more than three raster lines across the Landolt "C". As the number of lines across the "C" increases to five, there is a significant improvement in accuracy of identification.

• For alphanumeric characters, the 10, 12, 16, and 20 lines per in. conditions yield significantly more accurate character recognition than the 8 lines per in. condition. Character recognition accuracy improves as character size increases to 20 min arc, especially for resolutions of 8-12 lines per in. (Fig. 1).

• For silhouette recognition, as raster lines per symbol height increase, so does identification accuracy. Ninety percent accuracy is obtained with ten or more raster lines per symbol height when the minor dimension of the silhouette is vertical. (Fig. 2).

Repeatability/Comparison with Other Studies

The study reported three experiments where different types of stimuli (alphanumeric characters, Landolt "C's", and silhouettes) were used. All three experiments report similar findings, indicating that ten lines per symbol height is the minimum number of lines necessary for acceptable legibility on a raster scanned display. This finding is in general agreement with similar studies (Refs. 3, 4).

Constraints

• Different character or symbol sizes outside of the ranges tested might yield a different pattern of results.

• Results might be different for reading text strings as opposed to reading a single character.

• Results must be applied cautiously to displays other than raster-scanned, monochrome CRTs, and do not necessarily apply to computer-generated or other discrete, digitally driven raster systems.

• Results may be different for reading characters or identifying symbols presented with different luminances and contrasts or presented in suboptimal environments where other displays, vibration, or washout are present.

• Results may be different for light images on a dark background.

• Display systems using newer technology may not be subject to direct application of the data presented in this entry and will require empirical validation.

Key References

*1. Baker, C. H., & Nicholson, R. (1967, May). Raster scan parameters and target identification. *Proceedings of the 19th Annual National Aerospace Electronics Conference* (NAECON) (pp. 285-290). Dayton, OH: Institute of Electrical and Electronics Engineers.

2. Hemingway, J. C., & Erickson, R. A. (1969). Relative effects of raster scan lines and image subtense on symbol legibility of television. *Human Factors, 11*, 331-338.

3. Kinney, G. C. (1965, December). *Studies in display legibility* (MTP-21). Cambridge, MA: MITRE Corp.

4. Meister, D. (1984). *Human engineering data base for design and selection of cathode ray tube and other display systems* (NPRDC TR 84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

Cross References

1.602 Measurement of visual acuity;

1.615 Visual acuity: effect of viewing distance;

1.616 Visual acuity: effect of viewing distance and luminance level;

1.618 Visual acuity with target motion: effect of target velocity and orientation;

11.110 CRT scan line orientation: effect on symbol legibility;

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification;

11.208 Dot-matrix versus stroke-written symbols: effect on recognition

11.109 CRT Symbol Size, Viewing Angle, and Vertical Resolution: Effect on Identification Accuracy

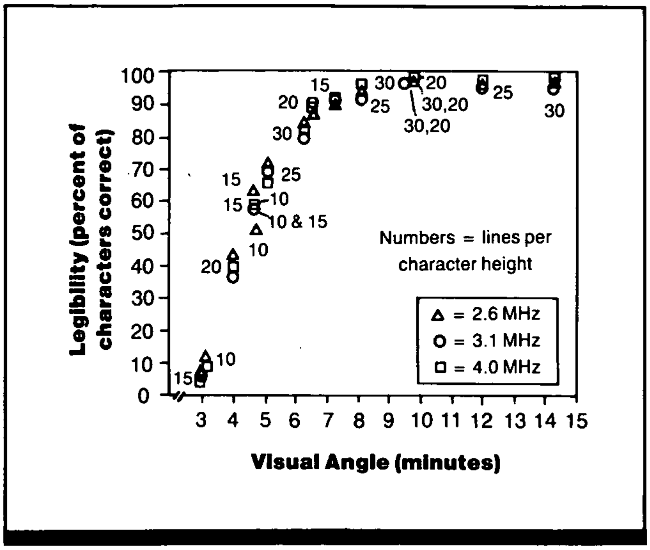


Figure 1. Average legibility at three bandwidth settings. (From Ref. 3)

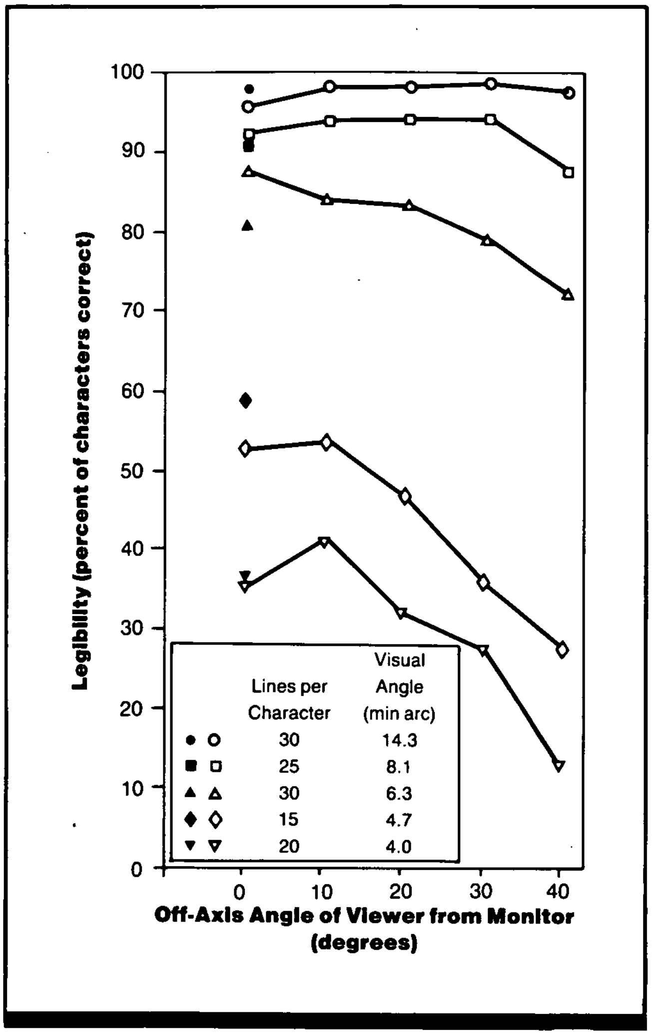


Figure 2. Average legibility as a function of off-axis angle for five representative test conditions. Solid symbols indicate data for standard tape; other data taken with special low-noise tape. (From Ref. 3)

Key Terms

Alphanumeric coding; analog television; character recognition; CRT displays; information display; monochrome displays; TV displays; vertical resolution

General Description

The many variables affecting character identification on CRT displays include angular size, off-axis viewing angle, and scan lines per character height. Percentage of characters correctly identified (legibility) is strongly influenced by the visual angle subtended by the characters (Ref. 3). Legibility increases with increasing angular character size. Off-axis viewing interacts with character size. With small characters, performance is reduced when the off-axis viewing angle is >20 deg. Performance studies also indicate that accuracy of character recognition is a function of the number of CRT scan lines per character height; legibility decreases when vertical resolution is <10 lines per character height. Figure 3 presents recommendations for CRT monitor size and other dimensions for worst-case classroom viewing conditions (30 deg off-axis viewing of a CRT monitor, 8 min arc of visual angle characters and a 6-m viewing distance).

Applications

Monochrome, raster-scanned television displays (e.g. multifunction displays) used for alphanumeric information display in nonvibrating, normal gravity environments.

Methods

Test Conditions

- Alphanumeric characters (eight rows of seven characters randomly selected from the capitalized alphabet of Manifold font, and the digits from 0-9) plus row numbers and page designators; 50% capital letters, 50% numbers
- Recorded with a 525-line Granger V1000 television camera having a GEC 8507 high-resolution vidicon; all stimuli recorded and played back from a Sony EV200 video recorder with Sony low-noise (V-11-60) 1-in. tape; displays presented via a Conrac (CQE-14/525/1029) 14-in. monitor with background luminance of 68.6 cd/m^2, stimulus luminance of 6.86 cd/m^2, and a modulation or Michelson contrast, $[(L_{max} - L_{min})/(L_{max} + L_{min})]$, of 0.82; stimuli presented with negative contrast (dark images on light background)
- Circular polarizing filter over display and non-reflective black paper on walls at key points to reduce reflective glare

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Procedure

- Within-subjects factorial design
- Independent variables: visual angle of stimuli, viewing angle, scan-lines of vertical resolution, bandwidth
- Dependent variables: characters per view and percent of characters correctly identified, as determined by computer from subject's reading and typed output
- Subject's task: read seven-character random alphanumeric display at an input/output (I/O) typewriter terminal; enter the perceived display characters at the terminal using the television display for visual feedback; procedure repeated until eight lines of characters entered, concluding a page; error corrections allowed at this point; procedure repeated for subsequent pages
- Data collected during one 5-hr session with frequent breaks
- 20 experienced female typists, ages 18-30; all had 20/20 or better visual acuity

Experimental Results

- Percent correct responses increases from about 10% accuracy with a character vertical visual angle of 4 min arc to 95% at 8 min arc, and to 98% at 14 min arc (Fig. 1).
- Percent correct responses is not significantly affected by vertical resolution over the range tested (15-30 scan lines per character height).
- The influence of off-axis viewing depends upon character size (Fig. 2). Legibility is relatively unaffected by viewing angle for larger (14.3 and 8.1 min arc) characters, but is reduced for the 20-deg or greater off-axis viewing conditions for small (4.0-6.3 min arc) characters.
- It is recommended that characters subtend a minimum of 8 min arc for off-axis viewing of 10-40 deg.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

A previous study (Ref. 4) also failed to find scan line per character vertical resolution effects within the range tested. Another source (Ref. 1) concludes that the minimum acceptable resolution is 10 scan lines per character height at a viewing distance of ~ 70 cm. Yet another investigation (Ref. 4) concludes that at least eight raster lines per character height and a character subtense of 10 min arc is necessary for adequate symbol legibility at ~70-cm viewing distance.

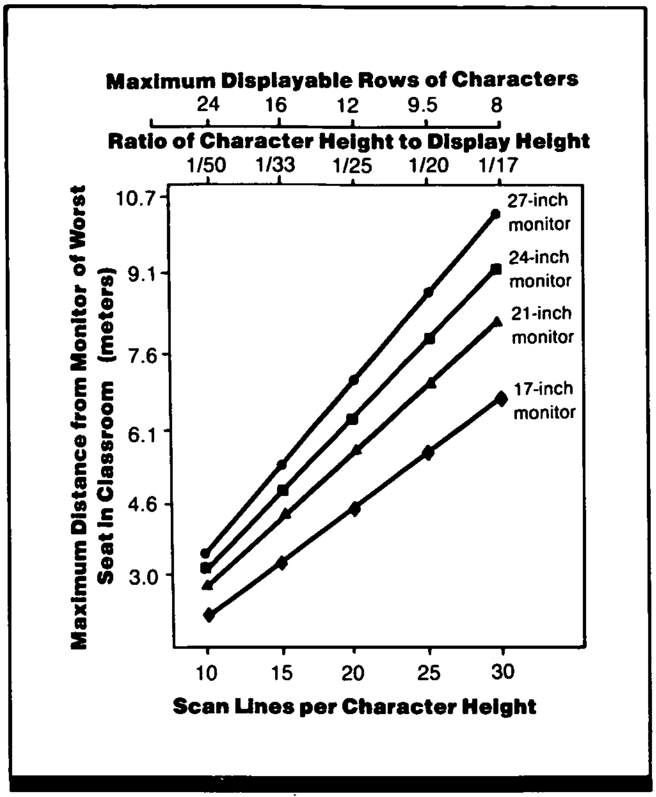


Figure 3. Maximum viewing distance for worst seat in classroom maintaining a minimal 8 min visual angle at the eye. (From Ref. 3)

Constraints

- Only one luminance level was used, and legibility would be expected to decrease at lower contrasts, especially for older subjects.
- Stimuli were random character strings rather than meaningful text. Legibility would be better in a more contextual task.
- Alphanumeric character set was of limited size (only some capital letters and numerals). A larger set would be expected to increase confusion and decrease legibility.
- Only one contrast (0.82) value was used: contrast would be expected to interact with other factors to change legibility.
- Results may be different for light images on a dark background.
- The surface of the display was probably a spherical section; results may not be directly applicable to displays with either cylindrical or flat surfaces.
- Newer technology displays may yield different results.
- By varying viewing distance, both symbol subtenses and angular size of the total display were changed together, so that the characters at ten times the background luminance were more of a glare source, i.e., further from the eye's adaptation luminance.

Key References

1. Baker, C. H., & Nicholson, R. (1967, May). Raster scan parameters and target identification. *Proceedings of the 19th Annual National Aerospace Electronics Conference* (pp. 285-290). Dayton, OH: Institute of Electrical and Electronics Engineers.

2. Hemingway, J. C., & Erickson, R. A. (1969). Relative effects of scan lines and image subtense on symbol legibility on television. *Human Factors, 11*, 331-338.

*3. Neal, A. S. (1968). Legibility requirements for educational television. *Information display, 5*, 39-44.

4. Siebert, W. F., Kosten, D. F., & Potter, J. R. (1959). A study of factors influencing the legibility of televised characters. *Journal of the Society of Motion Picture and Television Engineers, 68*, 467-472.

Cross References

11.103 Display surround luminance and subjective visual comfort;

11.108 Television display resolution: effect on time and accuracy for symbol identification;

11.118 Dot matrix displays: effect of symbol size and viewing distance on recognition;

11.209 Alphanumeric font and display legibility

11.110 CRT Scan Line Orientation: Effect on Symbol Legibility

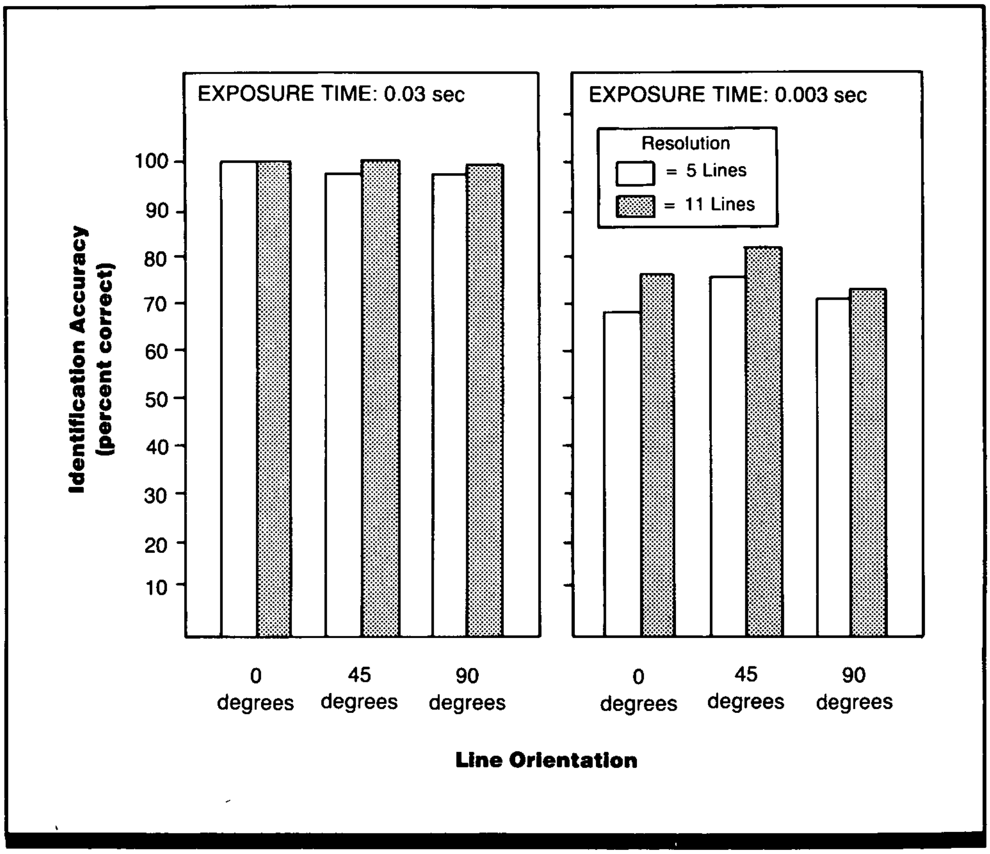


Figure 1. Letter identification accuracy as a function of scan line orientation. (From Ref. 3)

Key Terms

Alphanumeric displays; character recognition; CRT displays; information display; legibility; monochrome displays; scan lines; TV displays

General Description

The ability to read text as a function of the scan line orientation was tested in an experiment that used a simulated TV scan line technique. Results indicate that the scan line orientation (0, 45, and 90 deg with respect to the base of symbols) does not significantly affect the accuracy scores of subjects reading single characters. Another study (Ref. 1) shows that a horizontal orientation (0 deg) is preferred when a low bandwidth (1-2 MHz) is used. Scan-line orientation has little practical effect on legibility as long as the bandwidth is sufficiently high.

Methods

Test Conditions

- Capital letters of unspecified font presented using a tachistoscope; 152 cm viewing distance; letters 13 min arc of visual angle in height
- Stimuli were film negatives with alternate opaque and transparent lines; 5-line and 11-line negatives; 1:1 ratio of opaque to transparent strips; grid lines presented at 0, 45, and 90 deg to the base of the letters
- Letters presented for 0.03 and 0.003 sec
- Symbol luminance and contrast not specified but presumed adequate

Experimental Procedure

- Mixed design; each subject saw only one line-orientation condition, but saw stimuli at each exposure time and at each resolution
- Independent variables: line orientation, exposure time, resolution
- Dependent variables: symbol identification accuracy, response time
- Observer's task: verbalize letter name as quickly as possible
- 12 observers

Experimental Results

- No significant differences are evident among the three-line orientation conditions, as measured by response times and accuracy.
- Subjects make significantly more errors with shorter (0.003 sec) presentation times.
- Response time and accuracy are both poorer for the 5-line resolution condition than for the 11-line resolution condition.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Results from a similar study (Ref. 2) found a different pattern. Accuracy scores were significantly better with horizontally oriented (0 deg) raster lines than with a vertical (90 deg) orientation. These differences are more pronounced at lower bandwidths (1-2 MHz), and almost negligible (1-2% differences) at higher bandwidths (3-5 MHz).

Constraints

- This research used a simulation technique instead of an actual TV picture. Results might be different with presentations on a CRT.
- Results should not be generalized to scan angles other than those investigated.
- Results might be different for reading text strings than for single characters.
- Displays used were monochrome. Color display applications may not be subject to direct application of guidelines given in this entry and will require empirical validation.
- Results may differ with another type style or font.
- Extremely short exposure times in the study are not typical in actual equipment use.

Key References

1. Clauer, C. L. (1967). *Legibility analysis of television systems* (16.158). Los Gatos, CA: IBM.

2. Meister, D. (1984). *Human engineering data for design and selection of cathode ray tube and other display systems* (NPRDC-TR-84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

*3. Shurtleff, D., Botha, B., & Young, M. (1963, December). *Studies of display legibility: III. The effects of scan line orientation* (Working Paper W-6899). Bedford, MA: The MITRE Corporation. (DTIC No. AD633851)

Cross References

11.101 Judged image quality on CRT displays: effect of bandwidth and image motion;

11.108 Television display resolution: effect on time and accuracy for symbol identification;

11.109 CRT symbol size, viewing angle, and vertical resolution: effect on identification accuracy;

11.111 CRT symbol size and resolution: effect on legibility;

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification

11.111 CRT Symbol Size and Resolution: Effect on Legibility

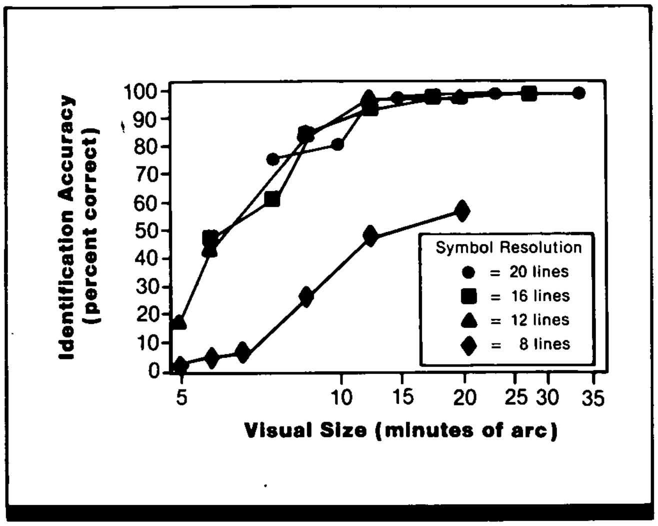


Figure 1. Accuracy of identification as a function of visual size and symbol resolution (number of scan lines). (Adapted from Ref. 3)

Key Terms

Alphanumeric coding; alphanumeric displays; analog television; character recognition; CRT displays; information display; legibility; monochrome displays; scan lines; TV displays

General Description

Preferred resolution for television-displayed characters is 10-12 scan lines per symbol height (Ref. 2). Symbol sizes of 12-15 min arc of visual angle produce the greatest recognition accuracy; accuracy measures are significantly lower with only eight lines of resolution.

Methods

Test Conditions

- 26 alpha and 10 numeric characters presented on a 525-line Miratel 35-cm video monitor
- Symbols presented in Leroy font with symbol width 75% of symbol height
- Symbol heights of 8, 12, 16, or 20 scan lines of vertical resolution
- Symbol sizes of 5, 6, 7, 9, 12, 20, and 27 min arc visual angle
- Symbol luminance 685 cd/m^2; background luminance of 68 cd/m^2
- Viewing distances 92-163 cm; viewing angle 0 deg
- Stimulus duration was 4 sec

Experimental Procedure

- Within-subjects design
- Independent variables: symbol height, resolution
- Dependent variable: identification accuracy
- Observer's task: identify characters when presented
- 8 observers

Experimental Results

- Accuracy is greater as lines of resolution increase; measures are not significantly different for resolution of 12, 16, or 20 lines. Symbol sizes of 12 min arc of visual angle or greater are required for high accuracy.

Variability

Two independent studies were conducted. Each indicates that the minimum acceptable vertical symbol resolution is 10 scan lines per symbol height.

Constraints

- Results might be different for reading text strings rather than single characters, or for viewing times shorter than 4 sec.
- Results might vary for different quality displays, different character styles, or different symbol-to-background contrasts. Modern flat-field, raster interlace, and spot wobble or dither techniques may result in better recognition and identification performance at less resolution (e.g., seven to eight lines) than shown in the figure.
- Results must be applied with caution to displays other than raster-scanned, monochrome CRTs with light symbols against a dark background.
- Display systems using newer technology may not be subject to direct application of the data presented in this entry and will require empirical validation.

Key References

1. Baker, C. H., & Nicholson, R. (1967, May). Raster scan parameters and target identification. In the *Proceedings of the 19th Annual National Aerospace Electronics Conference* (NAECON) (pp. 285-290). Dayton, OH: Institute of Electrical and Electronics Engineers (IEEE).

2. Meister, D. (1984). *Human engineering data base for design and selection of cathode ray tube and other display systems* (NPRDC-TR-84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

*3. Shurtleff, D. A. (1966, August). *Studies of display symbol legibility: II. Factors in the legibility of television displays* (ESD-TR-66-299). Bedford, MA: USAF Electronic Systems Division, Hanscom Air Force Base. (DTIC No. AD640571)

Cross References

11.112 CRT symbol size and stroke width: effect on legibility;

11.113 CRT symbol spacing: effect on identification accuracy;

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification;

11.208 Dot-matrix versus stroke-written symbols: effect on recognition

11.112 CRT Symbol Size and Stroke Width: Effect on Legibility

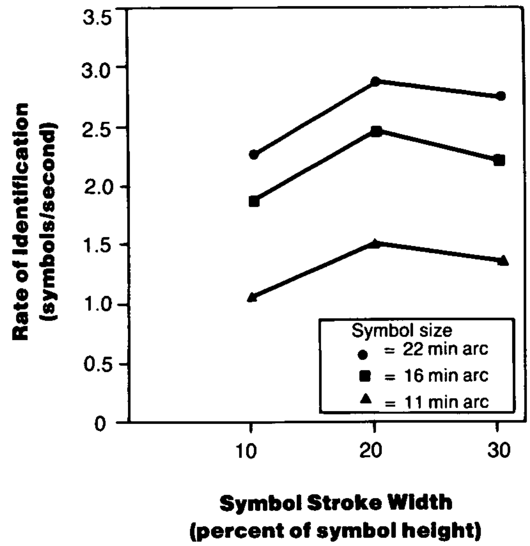


Figure 1. Relationships among capital letter stroke-width, visual size, and rate of identification. (Adapted from Ref. 1)

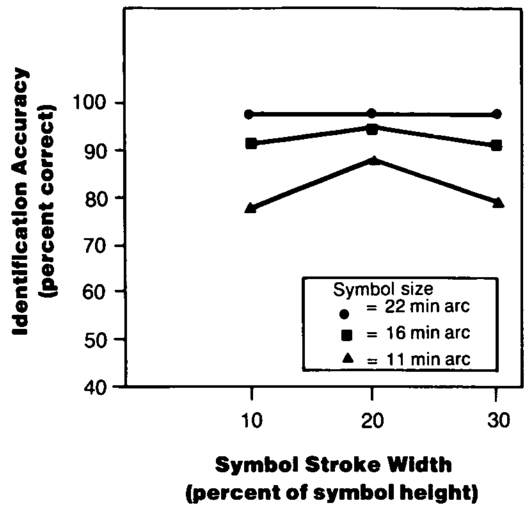


Figure 2. Relationships among capital letter stroke-width, visual size, and identification accuracy. (Adapted from Ref. 1)

Key Terms

Alphanumeric coding; alphanumeric displays; character recognition; CRT displays; information display; legibility; monochrome displays; raster scanned TV; TV displays

General Description

Symbol stroke width is usually expressed as a percent of the symbol's height. Using photographs for display simulation, an interaction is found when symbol size and stroke width are varied together and legibility is measured using reading accuracy scores. Characters are identified faster with 20% and 30% stroke widths than with a 10% stroke width (Fig. 1). Accuracy is best with medium and large characters (16-22 min arc of visual angle) at all stroke widths investigated (Figs. 1, 2). When small characters are used, an intermediate stroke width (20%) produces a higher identification rate. However, smaller characters produce lower overall accuracy scores (Fig. 2).

Methods

Test Conditions

- 26 capital letters, approximating 4, 6, and 8-1/2-point commercial type sizes; letter size changed by varying viewing distance; viewing distances: 25, 36, and 51 cm; resulting vertical visual angles subtended by letters: 11, 16, and 22 min arc; letter width 86% of letter height; three stroke widths: 10, 20, and 30% of symbol height; two interletter spacings: 35 and 63% of letter height
- Dark letters printed on three light-colored papers with red light reflectances of 26, 49, and 87%; test sheets 9.2 cm high by 10.8 cm wide
- Stimuli presented to subjects in light-tight booth; illumination provided by single spotlight fitted with Corning red glass filter No. 2403; illuminance at reading surface 0.9 lm/ft^2; headrest used to control viewing distance

Experimental Procedure

- Within-subjects design
- Independent variables: character height, character stroke width interletter spacing, background reflectance
- Dependent variables: accuracy of symbol identifications, response time
- Subject's task: identify letters
- 12 male observers

Experimental Results

- Characters with a stroke width of 20% of symbol height were identified correctly most often.
- Response accuracy is best with a large symbol height (22 min arc).
- Speed of symbol identification increases with symbol size. The 22 min arc symbol yields the fastest response.
- Inter-letter spacing yields no consistent influence on response accuracy or speed of symbol identification.
- The influence of reduced reflectance (and therefore symbol-to-background contrast) is minimized when other char-

acter legibility variables (character height and stroke width) are in acceptable ranges. When other character legibility variables are suboptimal, reduced contrast yields lower symbol identification accuracies and identification rates.

Variability

Results are generally consistent across four experiments reported in Ref. 1.

Constraints

- Different character sizes outside of the ranges tested might yield different results.
- Results might be different for reading meaningful text strings as opposed to random character sequences.
- Results might be different for actual CRT displays of information; these data were collected in a display simulation.
- Results apply only to dark symbols viewed against a light background.
- Applications of these data to displays using newer technology will require empirical validation.

Key References

*1. Crook, M. N., Hanson, J. A., & Weisz, A. (1954, March). *Legibility of type as determined by the combined effect of typographical variables and reflectance of background* (WADC-TR-53-441). Wright-Patterson AFB, OH: Wright Air Development Center. (DTIC No. AD043309)

2. Meister, D. (1984). *Human engineering data base for design and selection of cathode ray tube and other display systems* (NPRDC-TR-84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

Cross References

11.111 CRT symbol size and resolution: effect on legibility;

11.113 CRT symbol spacing: effect on identification accuracy;

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification;

11.208 Dot-matrix versus stroke-written symbols: effect on recognition

11.113 CRT Symbol Spacing: Effect on Identification Accuracy

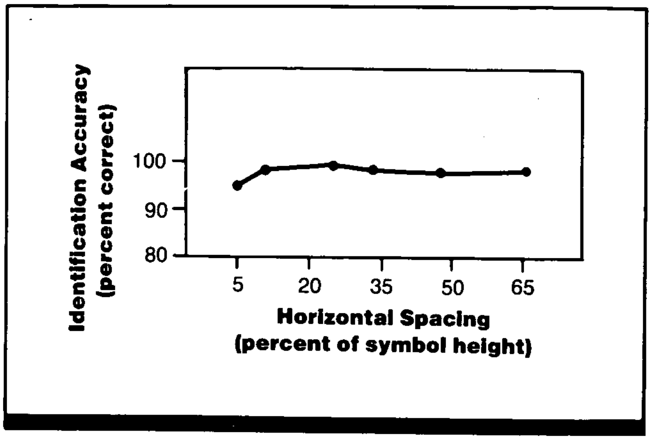


Figure 1. Identification accuracy as a function of horizontal spacing between symbols. (Adapted from Ref. 2)

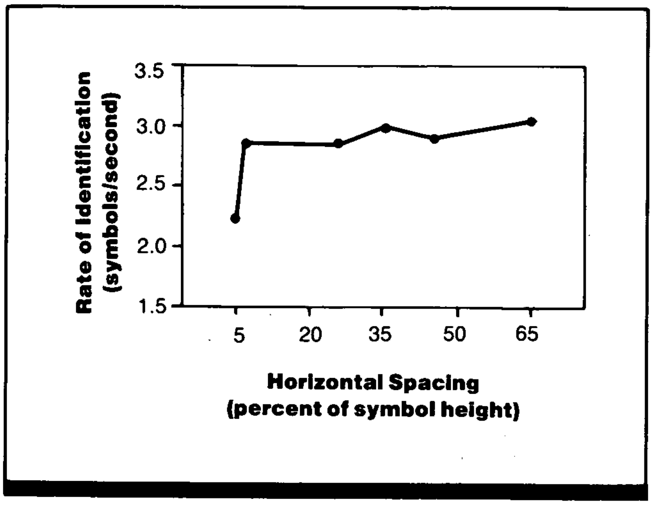


Figure 2. Identification rate as a function of horizontal spacing between symbols. (Adapted from Ref. 2)

Key Terms

Alphanumeric coding; alphanumeric displays; character recognition; CRT displays; dot matrix displays; flat panel displays; monochrome displays; TV displays

General Description

Laboratory research has shown that identification accuracy for characters presented on a television display is not affected by different horizontal spacings between characters (Fig. 1). A spacing of 8-10% of symbol height may be adequate for direct viewing of most displays. For off-axis viewing of 45 deg or more, horizontal spacing should be increased to 25-50% of symbol height for maximum legibility (Ref. 2). If suboptimal conditions are anticipated, symbol spacing should not be less than 25%. Spacing of 5-10% of symbol height yields the longest response time (fewest symbols per sec) by subjects reading characters on a television display (Fig. 2).

Methods

Test Conditions

- 36 letters and numerals; 7 x 9 dot-matrix format; height of symbols subtended a visual size of 9 min arc of visual angle at subject's eye; dot luminance of 61.74-68.6 cd/m²; symbol-to-background contrast ratio 10:1
- Symbol spacing: 5, 20, 35, 50, or 65% of symbol height
- Stimuli presented in a 3 x 3 array of symbols per observation
- Stimuli presented on Tektronix RM503 oscilloscope with a P-11 phosphor; room with overall luminance of 322 lux

Experimental Procedure

- Independent variable: symbol spacing
- Dependent variables: accuracy of symbol identification, response time
- Observer's task: verbally identify each symbol in normal reading fashion (right to left, top to bottom) as quickly and as accurately as possible
- 9 observers

Experimental Results

- All of the horizontal spacings tested produce essentially equal reading accuracy.
- Rate of symbol identification is higher with 8% or greater symbol spacing; identification rates are not significantly different for the 20, 35, 50, or 65% of symbol height conditions.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Reference 1 indicates that 10-15% of symbol height is an acceptable spacing distance for printed characters.

Constraints

- Fonts or character sizes different from those tested might yield a different pattern of results.
- Results might be different for reading text strings as opposed to single characters.
- Results must be cautiously used for displays other than monochrome raster-scanned CRTs. Results do not apply to color tubes used in monochrome mode.
- Results may be different for reading characters or identifying symbols presented in suboptimal environments where other displays, vibration, or washout are present.
- Direct application of the data presented in this entry to display systems using newer technology may not be appropriate; empirical validation may be required.
- Results may not apply to reverse polarity (dark symbols on light background) displays.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Crook, M. N., Hanson, J. A., & Weisz, A. (1954, March). *Legibility of type as determined by the combined effect of typographical variables and reflectance of background* (WADC- TR-53-441). Wright-Patterson AFB, OH: Wright Air Development Center. (DTIC No. AD043309)

*2. Meister, D. (1984). *Human engineering data base for design and selection of cathode ray tube and other display systems* (NPRDC-TR-84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

3. Shurtleff, D. A., & Alexander, P. J. (1973, March). *Symbol designs for the graphic symbol subset of the ASCII* (MTR-2456). Bedford, MA: The MITRE Corporation. (DTIC No. AD759807)

Cross References

11.111 CRT symbol size and resolution: effect on legibility;

11.112 CRT symbol size and stroke width: effect on legibility;

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification;

11.118 Dot-matrix displays: effect of symbol size and viewing distance on recognition;

11.208 Dot-matrix versus stroke-written symbols: effect on recognition

11.114 Display Element Size: Effect on Reading and Search Times

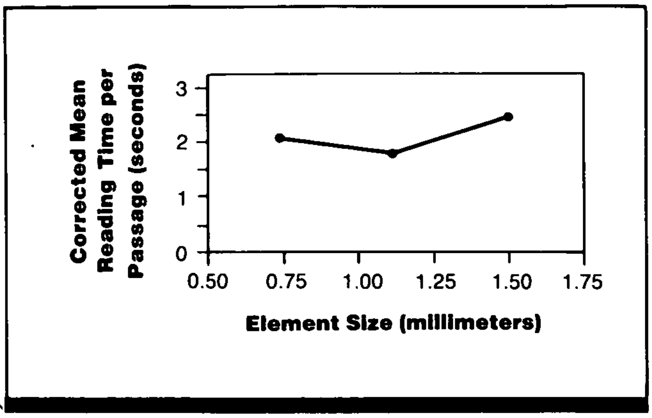


Figure 1. Effect of element size on reading time. (Adapted from Ref. 2)

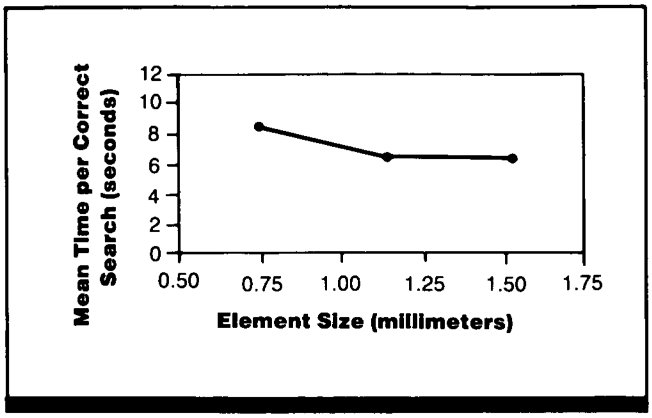


Figure 2. Effect of element size on random search time. (Adapted from Ref. 2)

Key Terms

Alphanumeric displays; CRT displays; dot matrix displays; flat panel displays; legibility; monochrome displays; reading; search time

General Description

The legibility of fixed element (pixel) displays is determined, in part, by the size, shape, and edge-to-edge spacing of the dots making up the characters. The effects of three element sizes on display reading and search times were investigated. For reading tasks such as alphanumeric paragraphs, it is possible to make element size (and corresponding character size) too large. Figure 1 shows that text reading times are shorter and comparable for characters of small and intermediate element sizes. For a search task, search times are shorter and comparable for the characters with intermediate and larger element sizes (Fig. 2), i.e., search performance is more efficient.

Methods

Test Conditions

- 36 alphanumeric characters, capital letters; composite of Lincoln/Mitre and two experimental fonts; characters generated using 5 x 7 dot matrices
- Element sizes of 0.76, 1.14, and 1.52 mm; interelement spacing to edge-to-edge/element size ratios of 0.5, 1.0, and 1.5; element shapes: square, horizontally elongated and vertically elongated; resulting character sizes ranged from 5.3-16.7 mm in width and from 7.6-24.3 mm in height, i.e., from ~16-56 min arc of visual angle in width and ~26-82 min arc in height
- Tektronix 4014-1 direct-view storage tube used to display symbols; green phosphor; average display background luminance 2 cd/m^2; character luminance 17 cd/m^2; display located in light-controlled booth
- Viewing distance 1.02 m; chin rest provided; response keyboard directly in front of subjects; tape recorder for verbal response recording

Experimental Procedure

- Within-observers design
- Independent variables: element size; interelement spacing to edge-to-edge/element size ratios; element shapes
- Dependent variables: text reading time corrected for baseline reading time, reading or target identification errors, average search time (sec) per error-free trial
- Observer's tasks: for text reading task, read one- or two-sentence passages from Tinker Speed-of-Reading Test as fast as possible, depressed response key when completed, and identified inappropriate word in text; for random search task, found desired alphanumeric character from among 71 characters randomly positioned on display, depressed response key, and identified character location in one of 12 display locations; for menu search task, searched three columns of eight words to locate desired word, and depressed response key
- 108 subjects; 61 males and 47 females

Experimental Results

- Only 9 random search errors and 17 menu search errors were made during 4,320 trials, i.e., errors were negligible.
- The 1.52-mm element size produces significantly longer text reading times ($p < 0.05$) than the 0.76- or 1.14-mm elements, which yield comparable reading times.
- Random search times are significantly ($p < 0.01$) longer for 0.76 mm element size, and are essentially equal for the other two sizes.
- Ambient illumination by element size interaction is significant ($p < 0.003$) for random search times, because mean search time is significantly longer ($p < 0.01$) for the 0.76-mm element at 700 lux than for any other size-illumination combination.
- Mean menu search time per correct trial is slightly, but significantly ($p < 0.01$), longer for 0.76-mm element size than for the other two element sizes.

Variability

No information on variability was given.

Constraints

- Different character sizes outside the ranges tested might yield different results.
- Results should be applied with caution to displays other than monochrome CRTs.
- Results may be different for reading text or searching for characters presented in suboptimal environments where other displays, vibration, or washout are present.
- Direct application of data presented in this entry to display systems using newer technology may be inappropriate and will require empirical validation.

Key References

1. Meister, D. (1984). *Human engineering data base for design and selection of cathode ray tube and other display systems* (NPRDC-TR-84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

*2. Snyder, H. L., & Maddox, M. E. (1978, October). *Information transfer from computer-generated dot-matrix displays* (ARO-12355.7-EL). Research Triangle Park, NC: U.S. Army Research Office. (DTIC No. ADA063505)

Cross References

11.116 Dot-matrix displays: effect of pixel size-spacing ratio on symbol reading time;

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification;

11.118 Dot-matrix displays: effect of symbol size and viewing distance on recognition;

11.207 Display element shape: effect on reading and search times;

11.209 Alphanumeric font and display legibility

11.115 Dot-Matrix Displays: Effect of Inter-Pixel Spacing on Character Identification

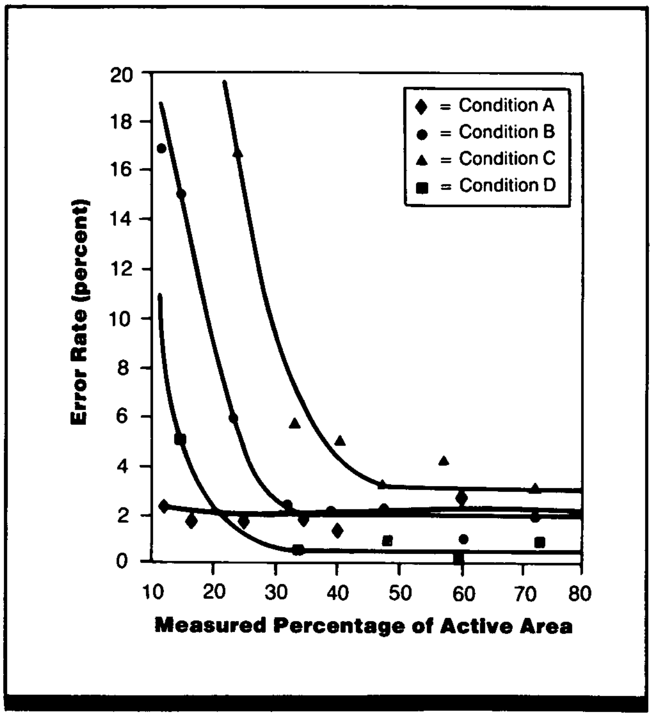


Figure 1. Reading error rate for 5 x 7 dot-matrix alphanumerics as a function of active area. See Table 1 for a description of test conditions. (From Ref. 2)

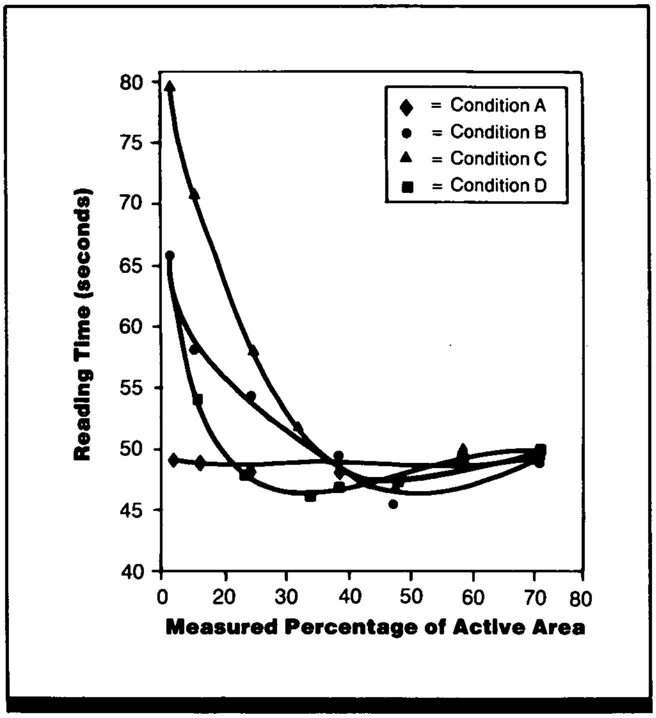


Figure 2. Reading time for 5 x 7 dot-matrix alphanumerics as a function of active area. See Table 1 for a description of test conditions. (From Ref. 2)

Key Terms

Alphanumeric displays; character recognition; CRT displays; dot matrix displays; flat panel displays; Lincoln-Mitre font; monochrome displays; reading error; TV displays

General Description

The active area of a TV display is the ratio of element size to the interelement spacing of the elements (or pixels) forming the characters. Data from a display simulation show that error rates and character identification times remain essentially unchanged for unstressed viewing conditions (comfortable reading distance and luminance) throughout the range of active display area from 11.9-71.6% of a character. For difficult viewing conditions (decreased symbol luminance, increased reading distance, and decreased contrast) experimental results indicate subject's acceptance threshold at the 30% active area level. Above this, effects of increase in active display area appear to be minimal. Below a 30% active area, error rates and character recognition times increase rapidly.

Methods

Test Conditions

- 36 dot-matrix alphanumerics, 5 x 7 dot matrices, Lincoln/Mitre font, 0.5 cm-height
- Eight assemblies of 108 characters, each having one of the following percentages of active display area: 11.9, 15.0, 23.9, 33.0, 38.5, 46.8, 58.7, 71.6 (active area percentage = $100\,A/d^2$, where A is the dot-matrix element area and d is the distance between equivalent locations on two adjacent dot-matrix elements); each presented to subject on a photographic print in a light-tight chamber with viewing port
- Four variations in test conditions: (A) unstressed, (B) decreased luminance, (C) decreased luminance and reading distance, and (D) decreased contrast and increased reading distance. (See Table 1)

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: percent-active areas, contrast, reading distances, background luminance
- Dependent variables: error rate, character identification time
- Observer's task: read aloud alphanumeric characters shown in photographic print
- All observers had 20/20 vision (corrected or uncorrected), normal color vision, did not wear bifocals; number of observers not reported

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- For unstressed conditions, error rate and character identification time remain relatively unchanged throughout the range of active area (11.9-71.6).
- For stressed conditions, at 30% active area or greater, performance is minimally reduced by decreased luminance, increased reading distance, or decreased contrast. However, below a 30% active area, error rate and identification time increase rapidly.
- In Condition D, the effect of reduced contrast on legibility appears to be offset by the increase in background luminance, and better performance is shown below the 30%-active area than for Conditions B and C.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Other researchers substantiate the increase in error rate as the percentage of active display area is reduced (Ref. 3), but the 30% threshold has not been reported elsewhere.

Constraints

- These results were obtained with a Lincoln/Mitre font, under specific uniform test conditions, and with photographs rather than light-emitting electronic display devices. Their application to emissive display devices must be made cautiously until further research is done with such devices.
- Percent-active area, emitter size, emitter spacing, symbol definition, symbol subtense, emitter luminance, and surround luminance are interrelated and must be considered together by the designer of a dot-matrix display.

Key References

1. Snyder, H. L., & Maddox, M. E. (1978, October). *Information transfer from computer-generated dot matrix displays* (ARO-12355.7-EL) Research Triangle Park, NC: U.S. Army Research Office. (DTIC No. ADA063505)

*2. Stein, I. H. (1980). The effects of the active area on the legibility of dot-matrix displays. *Proceedings of Society for Information Display*, *21*, 17-20.

3. Vanderkolk, R. J., Herman, J. A., & Hershberger, M. L. (1975). *Dot-matrix display symbology study* (AFFDL-TR-75-72). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory. (DTIC No. ADA016470)

Cross References

11.112 CRT symbol size and stroke width: effect on legibility;

11.113 CRT symbol spacing: effect on identification accuracy;

11.114 Display element size: effect on reading and search times;

11.116 Dot matrix displays: effect of pixel size-spacing ratio on symbol reading time;

11.117 Dot-Matrix displays: effect of matrix size on speed and accuracy of symbol identification;

11.207 Display element shape: effect on reading and search times;

11.208 Dot-Matrix versus stroke-written symbols: effect on recognition

Table 1. Test conditions.

	Condition A	Condition B	Condition C	Condition D
Background luminance (cd/m^2)	4.1	0.41	0.41	3.3
Reading distance (cm)	45.7	45.7	61.0	61.0
Contrast	7.5	7.5	7.5	3.2

11.116 Dot-Matrix Displays: Effect of Pixel Size-Spacing Ratio on Symbol Reading Time

Key Terms

Alphanumeric displays; CRT displays; dot-matrix displays; flat panel displays; legibility; monochrome displays; pixel resolution; reading

General Description

The legibility of fixed-element (pixel) displays is determined by the size, shape, and edge-to-edge spacing of the dots in the matrix. Active area of a television display is the ratio of element size to the interelement spacing. The figure shows that active area is directly related to reading time for passages of text. As the active area increases, the elements forming characters begin to appear more continuous, and alphanumeric characters are read or found more quickly.

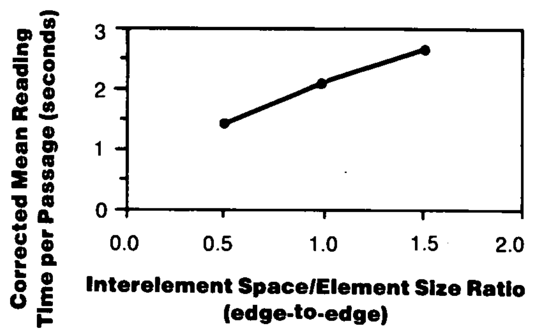


Figure 1. Effect of element-size-to-element-spacing ratio on text reading time. (Adapted from Ref. 2)

Methods

Test Conditions

- Thirty-six alphanumeric characters; letters all capitals; composite of Lincoln/Mitre and two experimental fonts; characters generated using 5 x 7 dot matrices
- Element size of 0.76, 1.14, and 1.52 mm; interelement spacing to edge-to-edge/element size ratios of 0.5, 1.0, or 1.5; element shapes: square, horizontally elongated, and vertically elongated; resulting character sizes range from 5.3-16.7 mm in width and from 7.6-24.3 mm in height; ambient illuminance 700 or 5.4 lux
- Tektronix 4014-1 direct-view storage tube used to display symbols; green phosphor; display background luminance 2 cd/m^2; character luminance 17 cd/m^2; display located in light controlled booth
- Viewing distance 1.0 m; chin rest provided; keyboard directly in front of subjects for responses; tape recorder for verbal responses

Experimental Procedure

- Factorial design
- Independent variables: element size, interelement spacing to edge-to-edge element size ratio, element shape
- Dependent variables: text reading time corrected for baseline reading time, reading or target identification errors, average search time (sec) per error-free trial
- Observer's task: for text-reading task, read one- or two-sentence passages from Tinker Speed-of-Reading Test as fast as possible, depressed response key when completed, and identified inappropriate word in text; for random search task, found desired alphanumeric character from among 71 characters randomly positioned on display, depressed response key, and identified character location in one of 12 display locations; for menu search task, searched three columns of eight words to locate desired word, and depressed response key
- 108 observers: 61 males and 47 females

Experimental Results

- Only nine random search errors and 17 menu search errors are made during 4,320 trials; numbers of both error types are inconsequential.
- 0.76- and 1.14-mm element sizes produce approximately equal reading times; both are shorter than for 1.52-mm element size condition ($p < 0.05$).
- The closer the elements are, the shorter the response times, with 0.5 interelement per element-size ratio yielding the highest response rate for both reading and search tasks.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Results of this study are consistent with what is known about raster-line visibility in raster-scanned television displays. Interelement spacing should be <50% of the element width (44% active area), and preferably much less (Ref. 1).

Constraints

- Results should be applied with caution to displays other than monochrome CRTs.
- Results may be different for reading characters or identifying symbols presented in suboptimal environments where other displays, vibration, or washout is present.
- Direct application of the data presented in this entry to display systems using newer technology may not be appropriate and will require empirical verification.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Meister, D. (1984). *Human engineering data base for design and selection of cathode ray tube and other display systems* (NPRDC-TR-84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

*2. Snyder, H. L., & Maddox, M. E. (1978, October). *Information transfer from computer-generated dot-matrix displays* (ARO 12355.7-EL). Research Triangle Park, NC: U. S. Army Research Office. (DTIC No. ADA063505)

Cross References

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification;

11.118 Dot-matrix displays: effect of symbol size and viewing distance on recognition;

11.207 Display element shape: effect on reading and search times;

11.209 Alphanumeric font and display legibility

11.117 Dot-Matrix Displays: Effect of Matrix Size on Speed and Accuracy of Symbol Identification

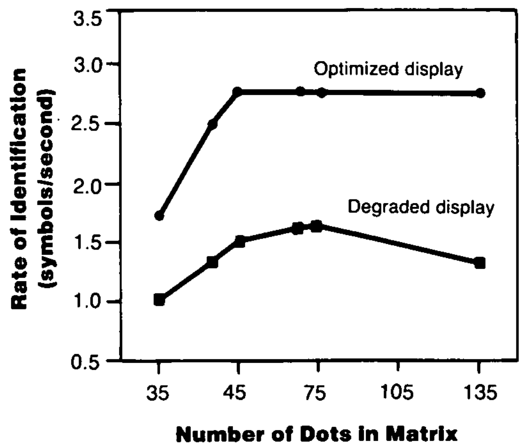


Figure 1. The relationship between number of dots in a matrix and rate of identification for optimized and degraded displays. (Adapted from Ref. 2)

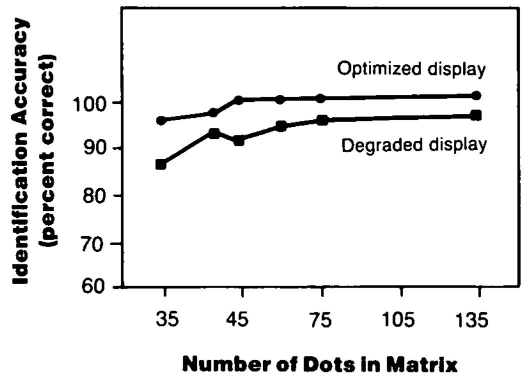


Figure 2. The relationship between number of dots in a matrix and identification accuracy for optimized and degraded displays. (Adapted from Ref. 2)

Key Terms

Alphanumeric displays; character recognition; CRT displays; digital displays; dot-matrix displays; flat panel displays; legibility; monochrome displays

General Description

The size of dot matrices affects the legibility of alphanumeric and special symbols presented on a CRT display. Rate of correct symbol identification improves gradually, but steadily, for each increase in number of dots in the matrix (Fig. 1). It is necessary to increase the matrix from 5 x 7 dots to 7 x 9 dots before a statistically significant improvement in correct identification occurs. When displays are degraded by any degree of character overprinting, performance deteriorates significantly for all matrix sizes.

Methods

Test Conditions

- 5 x 7, 5 x 9, 7 x 9, and 7 x 11 dot matrices used to construct 36 alphanumeric and six special symbols used in 407L and BUIC systems; matrix luminance ranged from 376-548 cd/m^2; symbol heights of 22 min arc of visual angle at observer's eye; symbol dimensions measured on the display: 0.43 cm high, 0.33 cm wide with 0.69-cm horizontal and vertical spacing; observer sat 71 cm away from CRT
- Degradation via overprinting: 0, 25, or 50% vertical overlap of two symbols
- Six unique, quasi-alphanumeric symbols presented simultaneously; arranged in two rows and three columns; symbols presented on Tektronix RM503 oscilloscope using either P7, P4, or P31 phosphors; fluorescent room illumination; 48 cd/m^2 illumination at scope face

Experimental Procedure

- Independent variables: dot-matrix display size; degradation condition
- Dependent variables: symbol identification accuracy, rate of identification
- Observer's task: learn names of symbols and pass a recognition test; depress a hand-held button to see symbols, depress button again when symbol recognized, while verbally responding; response time and response accuracies were recorded
- 24 observers

Experimental Results

- Characters are identified significantly more quickly and more accurately with larger matrices (7 x 9 and 7 x 11) than with the smallest matrix (5 x 7).
- Compared to the normal display conditions, all levels of overprinting significantly decrease the rate of correct symbol identification.
- The smaller the matrix, the greater the effects of overprinting.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Data from Ref. 4 support these finding (Figs. 1, 2). Reference 5 data indicate that a 7 x 9 matrix display yields faster response times and fewer errors than a 5 x 7 matrix for a comparable task.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Results might be different for reading text strings as opposed to single character displays.
- Results might vary for different kinds of displays with different symbols of different sizes or illuminations.
- Displays used were monochrome and of older technology. Application to newer technology display systems may require empirical validation.

Key References

1. Meister, D. (1984). *Human engineering data base for design and selection of cathode ray tube and other display systems* (NPRDC 84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

*2. Shurtleff, D. A. (1970, February). *Studies of display symbol legibility: XXIV. The relative legibility of special symbols formed from different matrices and the legibility of overprinted dot symbols* (ESD-TR-69-439). Bedford, MA: Hanscom AFB. (DTIC No. AD865413)

3. Snyder, H. L. (1980, July). *Human visual performance and flat panel display image quality* (HFL-80-1 ONR-80-1). Blacksburg, VA: Virginia Polytechnic Institute at State University. (DTIC No. ADA092685)

*4. Vartabedian, A. G. (1970, May). Effects of parameters of symbol formation of legibility. *Information Display, 1*.

Cross References

11.111 CRT symbol size and resolution: effect of legibility;

11.112 CRT symbol size and stroke width: effect on legibility;

11.113 CRT symbol spacing: effect on identification accuracy;

11.116 Dot-matrix displays: effect of pixel size-spacing ratio on symbol reading time;

11.118 Dot-matrix displays: effect of symbol size and viewing distance on recognition;

11.207 Display element shape: effect on reading and search times;

11.208 Dot-matrix versus stroke-written symbols: effect on recognition;

11.209 Alphanumeric font and display legibility

11.118 Dot-Matrix Displays: Effect of Symbol Size and Viewing Distance on Recognition

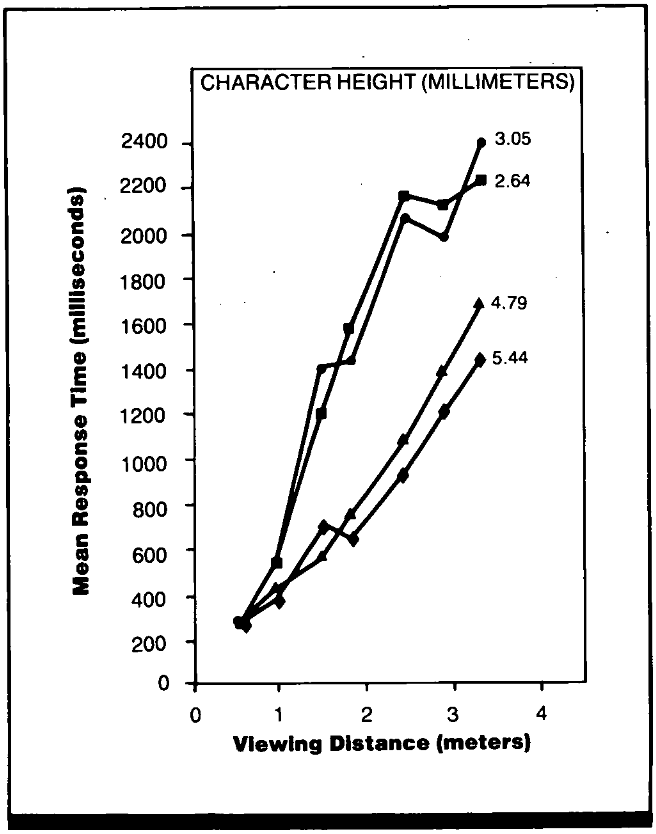


Figure 1. Effects of viewing distance and character size on response time. (From Ref. 2)

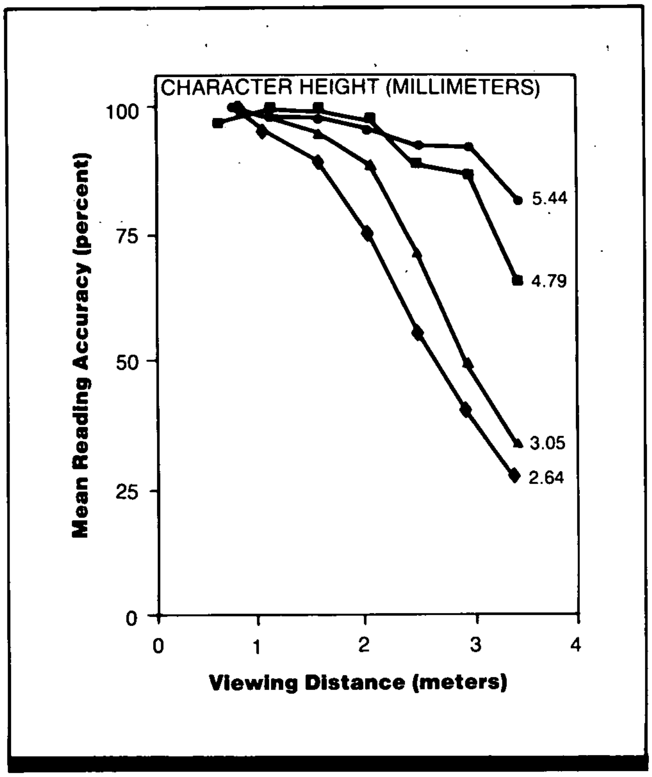


Figure 2. Effects of character size and viewing distance on reading accuracy. (From Ref. 2)

Key Terms

Alphanumeric displays; character recognition; CRT displays; dot matrix displays; legibility; monochrome displays; reading; TV displays

General Description

Research on the effects of viewing distance on response times and the accuracy of reading alphanumeric characters on a CRT display shows that subjects read more quickly at closer viewing distances (<1 m) than at greater viewing distances (3-4 m) and when larger characters (4.8 or 5.4 mm vertical height) are used (Fig. 1).

Character identification errors also decrease at closer viewing distances (≤1 m) and when larger characters (4.8 or 5.4 mm vertical height) are used (Fig. 2).

Methods

Test Conditions

- 36 alphanumeric characters, capital letters; Lincoln-Mitre font; character sizes from 2.6-5.4 mm vertically at screen; viewing distance: 0.6, 1.1, 1.5, 2.0, 2.4, 2.9, and 3.4 m
- Vertical visual angles subtended by characters at different viewing distances: 2.7-30.6 min arc of visual angle; three character luminances: 8, 27, and 80 cd/m2
- Information presented on a Tektronix 4014-1 display using a 7 x 9 dot-matrix format; green phosphor; located in a dark room

Experimental Procedure

- Within-subjects
- Independent variables: viewing distance, character size, character luminance
- Dependent variables: identification accuracy, response time
- Observer's task: press a hand-held button to display alphanumeric and then press the same button again when character recognized; screen then illuminated at random points to control for after-image as observer verbalized response
- 6 observers, 3 males and 3 females

Experimental Results

- More character identification errors ($p < 0.001$) occur at larger viewing distances (Fig. 2). The effect was strongest for smaller character sizes (2.6 and 3.0 mm).
- Generally, fewer character identification errors ($p < 0.001$) occur as character size increases. The greatest improvement occurs when character size increases from 3.0-4.8 mm.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

• Increasing character luminance results in significant ($p < 0.005$) but small improvements in character identification accuracy.
• Response times (Fig. 1) decrease with increases in character size ($p < 0.10$).
• Response times are greater for longer viewing distances than for shorter distances ($p < 0.001$).

Variability

No information on variability was given.

Constraints

• Reading accuracies and response times may be different for strings of alphanumeric characters and for different types of displays using different character styles, sizes, luminances, or ambient illuminations.
• Display used was monochrome. Color display applications will require empirical validation.

Key References

1. Meister, D. (1984). *Human engineering data base for design and selection for cathode ray tube and other display systems* (NPRDC-TR-84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

*2. Snyder, H. L., & Maddox, M. E. (1978, October). *Information transfer from computer-generated dot-matrix displays* (ARO-12355.7-EL). Research Triangle Park, NC: U.S. Army Research Office. (DTIC No. ADA063505)

Cross References

11.102 Electro-luminescent displays: minimum and preferred symbol luminances;

11.112 CRT symbol size and stroke width: effect on legibility;

11.114 Display element size: effect on reading and search times;

11.116 Dot-matrix displays: effect of pixel size-spacing ratio on symbol reading time;

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification

11.119 Estimation of the Number of Perceptible Gray Levels

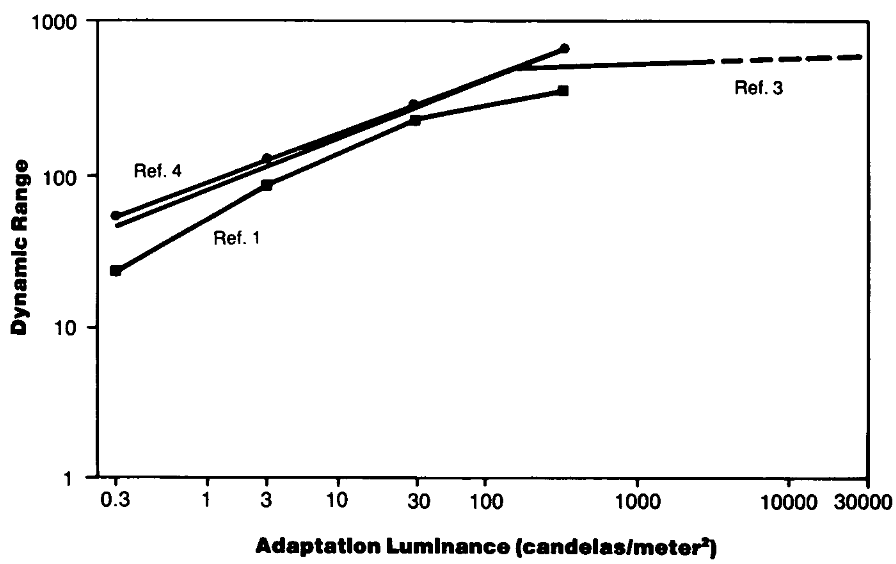


Figure 1. Instantaneous dynamic range of the eye as a function of the adaptation luminance. (From Ref. 2)

Key Terms

Contrast sensitivity; CRT displays; gray levels; information portrayal; modulation sensitivity; reconnaissance; target acquisition; target detection; TV displays; visual dynamic range; visual simulation

General Description

Operators using a CRT detect targets quicker as the number of perceivable gray levels in the display increases (CRef. 7.604). Two values are necessary to determine the number of perceptible gray levels: (1) the instantaneous dynamic range, which is the ratio of maximum to minimum luminance, given the adaption level of the eye; and (2) the demand modulation, which is the modulation necessary to discriminate between two adjacent gray areas at a particular spatial frequency.

The instantaneous dynamic range Z of the eye can be calculated from Fig. 1 if one knows the luminance value that has been used to adapt the eye. For example, an adaptation luminance level of 31.83 cd/m^2 (10 mL) yields an instantaneous dynamic range of ~200:1, and an adaptation level of 3000 cd/m^2 yields a range of ~550:1. (The dynamic range of the display can also be calculated by dividing the highlight luminance by the "black" level luminance; the dynamic range of the display also limits the number of perceptible gray levels.)

The demand modulation M_D for a given spatial frequency can be read from the y-axis in Fig. 2; the y-axis value is the modulation threshold times a factor of 1.6 (empirically determined) to yield a threshold that is "comfortable" for the observer.

The values for the instantaneous dynamic range Z and the demand modulation M_D are used in the formula

Number of gray levels (N) =
$\{\text{Log}_{10} Z/\text{Log}_{10}[(1+M_D)/(1-M_D)]\}+1$

Inserting 550 for Z and 0.017 for M_D Yields

$$N = \{\text{Log}_{10} 550/\text{Log}_{10}[(1+0.017)/(1-0.017)]\}+1$$
$$= [(\text{Log}_{10} 550)/(\text{Log}_{10} 1.034588)] + 1$$
$$= 186.6 \text{ gray levels}$$

Thus, there are 186.6 perceptible gray levels at an adaptation luminance of 3000 cd/m^2 with a spatial frequency of 20 cycles/deg. For any set of display conditions, the number of perceptible gray levels may be calculated across all spatial frequencies. The log of the number of perceptible gray levels can be used as an index of display quality.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Two assumptions are made for the process: (1) In the example with 3000 cd/m^2 luminance, it is assumed that the upper luminance level of 3000 cd/m^2 and the adaptation level are equal and (2) the demand modulation is assumed to be the same at all luminance levels of the dynamic range.
• The adaptation luminance is extremely influential, as increasing the adaptation level increases the dynamic range and thus increases the number of gray levels.
• Modulation thresholds (Fig. 2) should be empirically checked for the design situation.
• The formula is very sensitive, particularly at extreme values. In the example with 0.017 demand modulation, the denominator is $\log_{10}1.03459$; rounding to two decimal places and therefore dividing by $\log_{10}1.03$ changes the results from 186.6 to 214.5.
• As M_D approaches zero, the number of gray levels increases very rapidly as the formula approaches division by zero.
• Although the formula may be useful for comparisons of the relative number of gray levels, there is no reported validation of whether the formula yields values that correspond to the actual number of gray levels that can be perceived in a given situation (CRef. 7.604).

Key References

1. Arbribat, M. (1935). Sur le rendu photographique des luminosités. *Reun. Inst. Opt.*, *6*, 3rd Symposium.

*2. Carel, W. L., Herman, J. A., & Olzak, L. A. (1978). *Design criteria for imaging sensor displays* (ONR-CR213-107-1F). Washington, DC: Office of Naval Research. (DTIC No. ADA055411)

3. Nutting, P. G. (1916). Effects of brightness and contrast in vision. *Transactions of Illuminating Engineering Society*, *11*, 939-946.

4. Pitt, F. H. G. (1945). The nature of normal trichromatic and dicromatic vision. *Proceedings of the Royal Society*, *3*, 132.

5. Rogers, J. G., & Carel, W. L. (1973). *Development of design criteria for sensor displays* (HAC-REF-C6619). Culver City, CA: Hughes Aircraft Co. (DTIC No. AD774725)

Cross References

1.629 Contrast sensitivity: effect of field size;

1.630 Contrast sensitivity: effect of spatial frequency composition;

1.636 Contrast sensitivity: effect of visual field location for circular targets of varying size;

1.642 Contrast sensitivity: effect of border gradient;

1.653 Threshold models of visual target detection;

1.654 Continous-function models of visual target detection;

7.604 Effect of number of displayed gray levels on target acquisition

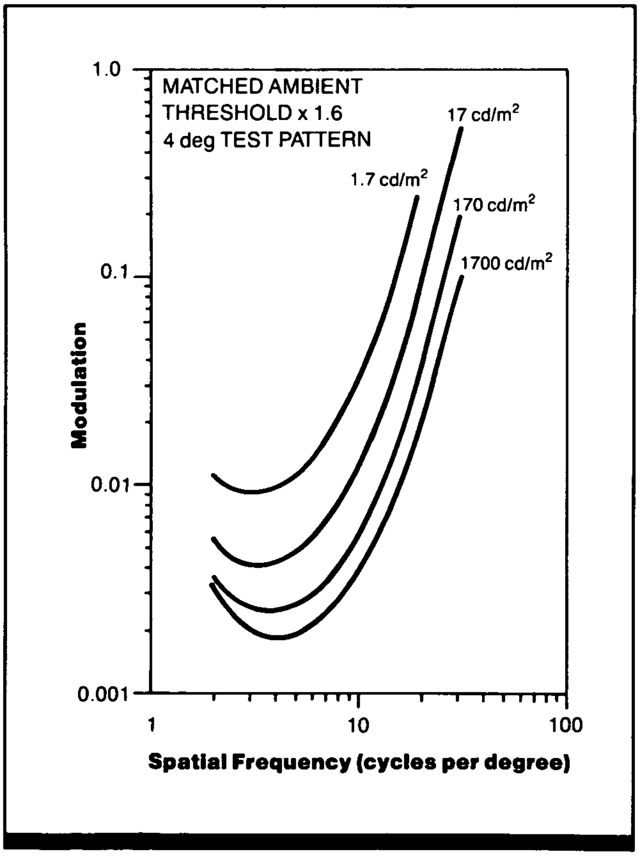


Figure 2. Modulation sensitivity function. Modulation values (threshold values times 1.6 comfort factor) as a function of spatial frequency. The curves are for four different luminance values. (From Ref. 2)

11.120 Perceived Flicker for CRT Phosphors of Varying Persistence

Key Terms

Critical flicker fusion; CRT displays; display persistence; phosphor persistence

General Description

The presence of flicker in CRT displays is much less prevalent than predicted by laboratory studies of flicker because of the persistence of the CRT phosphors. The relative amount of flicker is related to the persistence characteristics of the phosphor.

Applications

Flicker in CRT displays can be reduced by using high-persistence phosphors.

Methods

Test Conditions

- 0.36-0.44 min arc circular stimulus; 34, 110, or 340 cd/m^2 mean luminance
- Viewing distance 30-38 cm
- Gray surround illuminated to 10 cd/m^2
- P1, P4, P7, P12, P20, P28, and P31 phosphors tested
- Sine-wave and pulse modulation

Experimental Procedure

- Method of adjustment
- Independent variables: type of phosphor, stimulus luminance, sine-wave and pulse modulation, degree of modulation
- Dependent variable: flicker threshold
- Observer's task: adjust modulation of CRT to locate point between flicker and steady brightness
- 1-4 observers for each phosphor

Experimental Results

- Relative amount of flicker is related to the phosphor decay function but is also dependent upon refresh rate.
- With sine-wave modulation, phosphor P20 produced the least amount of flicker, and phosphor P31 produced the most flicker.
- With pulse modulation, P12 produced the least amount of flicker, and P20 produced the most.
- With sine-wave modulation and a flash rate >15 Hz, flicker perception increased with increased luminance; when the flash rate was <15 Hz, flicker tended to be more easily perceived as luminance decreased.

Variability

Thresholds varied by ~2 Hz when the same conditions were repeated during the course of a year.

Constraints

- Critical flicker frequency is affected by level of adaptation, size, and brightness of the surround, age, and color-vision defects.

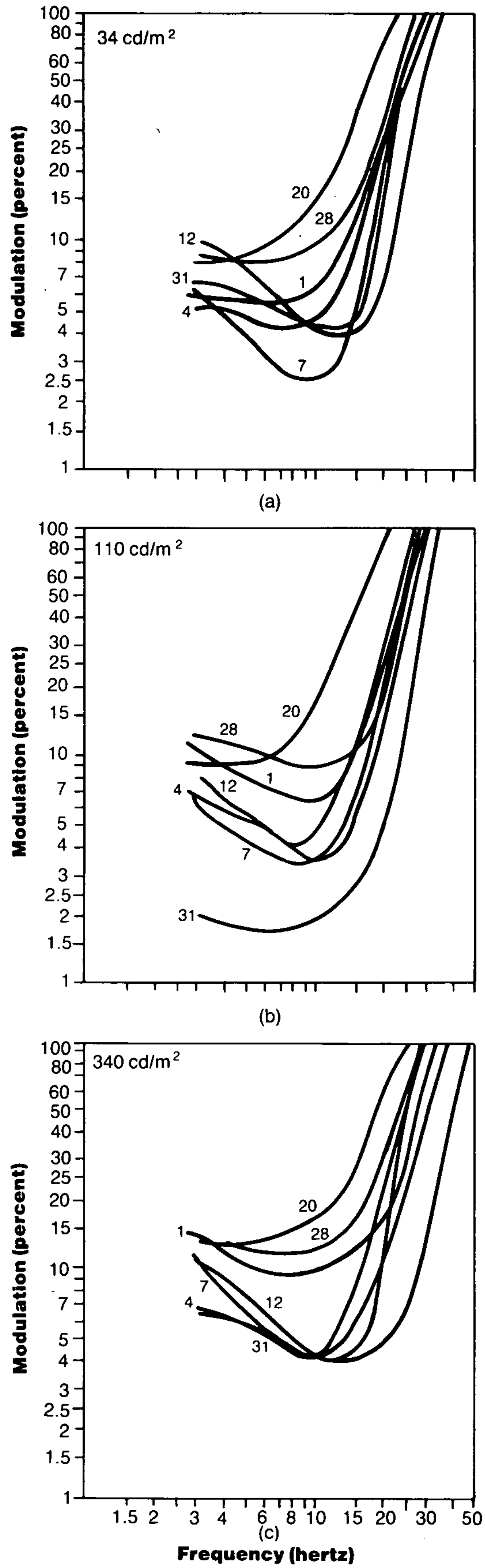


Figure 1. Critical flicker frequency as a function of the sine-wave modulation of test stimuli produced by different CRT phosphors (P1, P4, P7, P12, P20, P28, and P31) at mean stimulus luminances of (a) 34, (b) 110, and (c) 340 cd/m^2. The curves are the mean of 4 observers for P1, 3 observers for P4 and P7, and 1 observer for the others. (From Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Turnage, R. E., Jr. (1966). The perception of flicker in cathode ray tube displays. *Information Display*, *3*, 38-52

Cross References

1.501 Factors affecting sensitivity to flicker;

1.503 Flicker sensitivity: effect of flicker frequency and luminance level;

1.504 Flicker sensitivity: effect of dark adapation for targets at different visual field locations;

1.505 Flicker sensitivity: effect of type of target and luminance level;

1.506 Flicker sensitivity: effect of target size and surround;

1.508 Flicker sensitivity: effect of target spatial frequency;

1.510 Detection and discrimination of flicker rate;

11.122 Flicker thresholds for various cathods ray tube phosphors

11.121 CRT-Image Unsteadiness: Effect on Judged Picture Quality

Key Terms

CRT displays; image instability; image quality; picture quality

General Description

Using 16mm color motion-picture film for CRT viewing (e.g., television presentations) is often unsatisfactory because of image unsteadiness. Judged picture quality increases (as shown by lower parameter values in Fig. 1) as amplitude of movement decreases. In addition, increasing the period of movement (i.e., decreasing frequency) leads to an improvement in judged picture quality.

Methods

Test Conditions

- CRT displays of typical scenes found on commercial TV (using mainly stationary scenes and a fixed camera) were made unsteady in both horizontal and vertical axes
- Viewing system not described; probably standard British 625-TV-line-system with 2:1 interlace and 1/25-sec frame time
- Normal ambient light level in viewing room; highlight luminance not reported
- Observers were typical distance from display (six times the height of the picture)
- For each observer judgment, unsteady test picture alternated (10-sec presentation) with steady referent picture (10-sec presentation)
- Period of movement disturbance was 0.08, 0.25, 0.50, 1.0, 1.7, or 3.3 sec
- Peak-to-peak amplitude of movement (percent of picture height) ranged from 0.05-0.80%
- Subjects used European Broadcasting Union six-point Picture Impairment Scale (EBU-PIS) to rate picture degradation: 1—imperceptible; 2—just perceptible; 3—definitely perceptible but not disturbing; 4—somewhat objectionable; 5—definitely objectionable; and 6—unusable

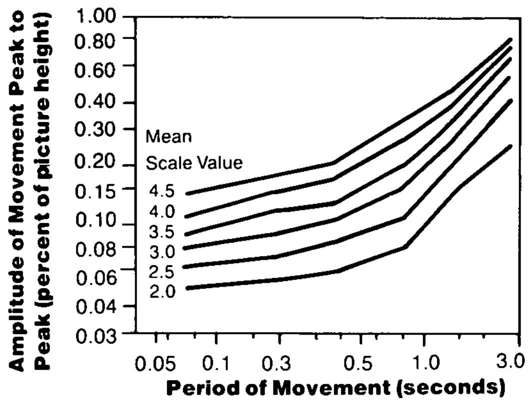


Figure 1. Effect of image unsteadiness on judgment of CRT picture quality. Amplitude of movement is plotted as a function of period of movement with judged image degradation as the parameter. (From Ref. 1, adapted from Ref. 2)

Experimental Procedure

- Independent variables: period of movement disturbance, amplitude of movement disturbance, axis of disturbance
- Dependent variable: judged degree of degradation of unsteady picture as compared with referent picture
- Observer's task: judge amount of degradation in test picture on the six-point European Broadcasting Union Picture Impairment Scale
- 20 observers, with an unknown amount of practice

Experimental Results

- Typical 16mm color negative film provides television images that are impaired and may be rated "definitely objectionable," even when the film is used in a high-quality professional movie camera.
- The effects of horizontal and vertical disturbances are similar; consequently, the combined results are reported.
- For any given period of movement, increased amplitude of movement of an unsteady television image produces more judged image degradation.
- For any given amplitude of movement, judged degradation decreases with increasing period of movement (i.e., decreasing frequency).

Variability

No information on variability was given.

Constraints

- Many factors (such as amplitude and period of movement, and response biases) can influence judged unsteadiness and must be considered in applying these results to other viewing conditions.

Repeatability/Comparison with Other Studies

When a moving object covered ~1/2 of the picture area, observers tolerated disturbances 40% greater than for the still pictures (CRef. 11.101).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Farrell, R. J., & Booth, J. M. (1984). *Design handbook for imagery interpretation equipment.* Seattle, WA: Boeing Aerospace Co.

*2. Wood, C. B. B., Sanders, J. R., & Wright, D. T. (1971). Image unsteadiness in 16mm film for television. *Journal of the Society of Motion Picture and Television Engineers, 80*, 812-818.

Cross References

10.410 Minimum amplitudes of vibration affecting vision;

11.101 Judged image quality on CRT displays: effect of bandwidth and image motion;

11.122 Flicker thresholds for various cathode ray tube phosphors

11.122 Flicker Thresholds for Various Cathode Ray Tube Phosphors

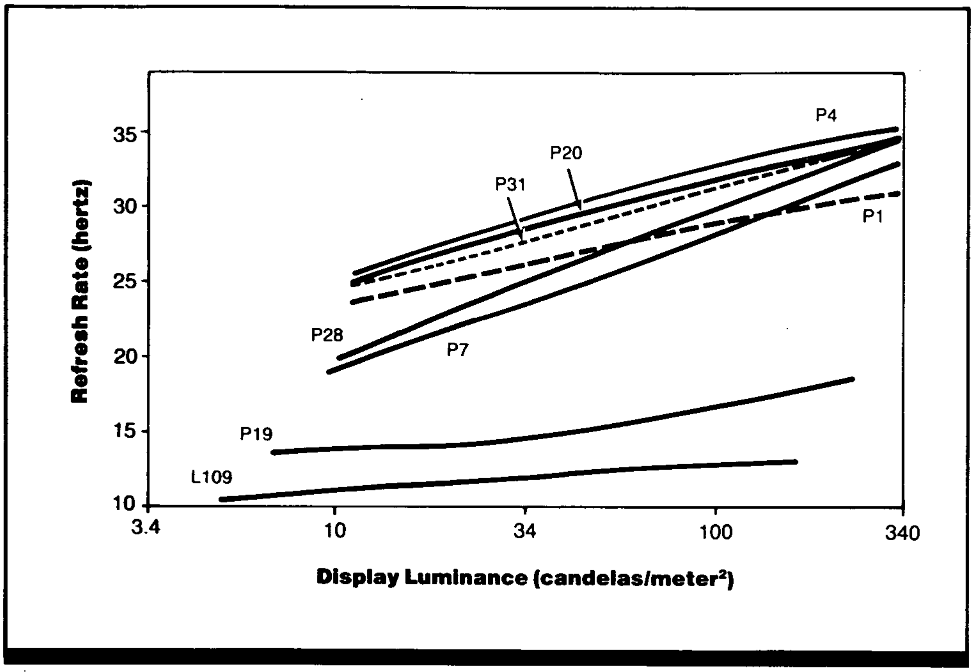


Figure 1. Flicker threshold of average observer for various phosphors. (From Ref. 1)

Key Terms

Critical flicker frequency; CRT displays; display persistence

General Description

Critical flicker frequency is defined as the lowest frequency at which a light will be perceived as anything but a steady light. Figure 1 displays flicker threshold as a function of display luminance for several common phosphors used with cathode ray tube (CRT) displays. For different phosphors, different refresh rate values are needed to maintain a similar critical flicker threshold. Flicker perception in the fovea can be eliminated from most electronic displays if the refresh rate is 35 Hz or more. For peripheral viewing a 47-Hz rate must be attained to eliminate flicker (Ref. 1). Flicker in CRTs cannot be noticed at a 60-Hz refresh rate unless display luminance exceeds 620 cd/m^2. Different displays require different refresh rates to eliminate flicker, but it is generally agreed that displays with <20-Hz presentations are usually quite annoying to the observer. Refresh rates between 7 and 15 Hz may result in disorientation or confusion (Ref. 5).

Constraints

- Foveal flicker thresholds are higher than peripheral thresholds for the same phosphor and luminance level (Ref. 1).
- Results may be different for types of phosphors not considered here.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Bryden, J. E. (1966). Some notes on measuring performance of phosphors used on CRT displays. *Seventh Annual SID Symposium*. Boston, MA: Society for Information Display.

2. Bryden, J. E. (1969). Design considerations for computer driven CRT displays. *Computer Design*, *8*, 38-46.

3. Laycock, J., & Chorley, R. A. (1980). The electro-optical display/visual system interface: Human factors concerns (RAE-TM-FS-305). Farnborough, Hants, U.K.: Royal Aircraft Establishment.

*4. Meister, D. (1984). *Human engineering data base for design and selection of cathode ray tube and other display systems* (NPRDC 84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. ADA145704)

5. Poole, H. H. (1966). *Fundamentals of display systems*. New York: Spartan Books.

Cross References

1.501 Factors affecting sensitivity to flicker;

1.503 Flicker sensitivity: effect of flicker frequency and luminance level;

1.504 Flicker sensitivity: effect of dark adaptation for targets at different visual field locations;

1.505 Flicker sensitivity: effect of type of target and luminance level;

1.506 Flicker sensitivity: effect of target size and surround;

1.508 Flicker sensitivity: effect of target spatial frequency;

1.510 Detection and discrimination of flicker rate;

11.120 Perceived flicker for CRT phosphors of varying persistence

11.123 Colored Light-Emitting Diodes: Use of Red or Green in High Ambient Illumination

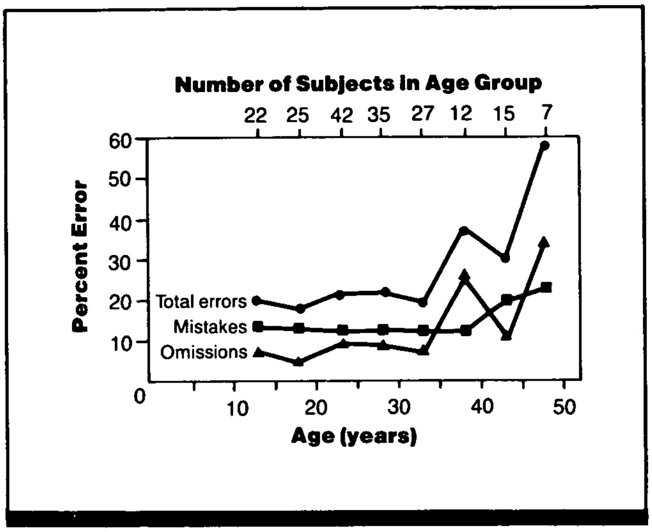


Figure 1. Dependence of performance on age (80,000-lux display) for subjects with normal vision (Exp. 1). (From Ref. 2)

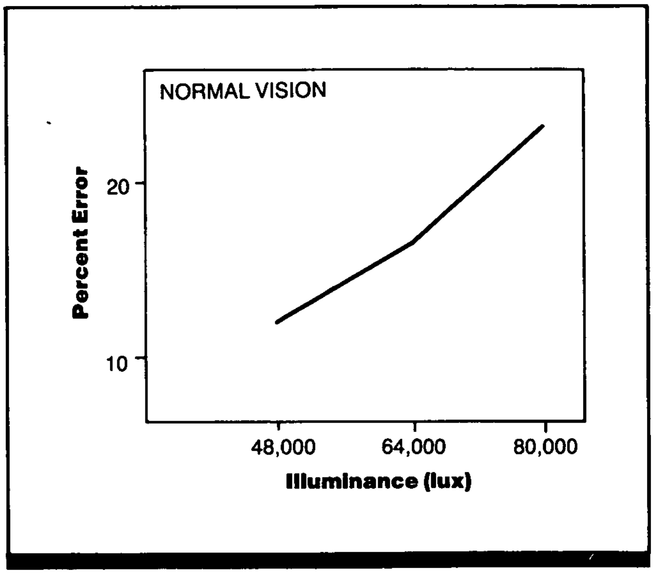


Figure 2. Error rate as a function of illuminance (Exp. 1). (From Ref. 2)

Key Terms

Alphanumeric displays; color contrast; color displays; dot-matrix displays; electro-luminescent displays; flat panel displays; LED displays; solid-state displays

General Description

A series of experiments (Ref. 2) on the ability to read actual and simulated light-emitting diode (LED) displays of alphanumeric characters under high (up to 10^5 lux) filtered incandescent illuminance, examined effects of color of presentation, age and sex of observers, dot element size, and ambient illumination. Red displays produce lower rates and fewer omission errors than green displays (Table 1). This may be due to the illuminance color temperature, which had maximum luminous intensity in the yellow-green region, thus reducing symbol-to-background color contrast for the green display. Observers more than ~35 yrs old make considerably more errors and omissions (Fig. 1), but observers sex does not affect performance. Characters made from larger dots are read more accurately, even though the illuminance of larger dots is one-half that of smaller dots (Table 2), because of the more continuous appearance of characters made of larger elements. Error rates increase with increases in ambient illumination (and associated lower symbol-to-background contrasts) within the range examined (Fig. 2).

Methods

Test Conditions

- Stimuli presented in light-controlled booth; adaptation illuminance by two banks of eight 1-kW incandescent lamps each; display illuminance by two banks of eight 1-kW incandescent lamps each, both filtered; peak illuminance in yellow-green region; viewing distance 75 cm
- Experiment 1 stimuli were sets of four randomly selected alphanumeric characters displayed using 5 x 7 LED dot-matrix display of red GaAs/P diodes; emission peaking at 660 nm; font not specified; character height 3 mm; average character luminance 100 cd/m²; illuminance 48,000, 64,000 or 80,000 lux
- Experiment 2 stimuli were rear-projected alphanumeric characters presented for 0.7 sec; 5 x 7 dot-matrix, Huddleston font, character height 4 mm; red character emissive peak at 660 nm; green character emissive peak not specified; character average illuminance 144 cd/m² for smaller (size unspecified) dot-elements; 77 cd/m² for larger elements (each dot twice area of smaller dot element); dot-space ratio 1:1 for smaller dot size; illuminance 10^5 lux
- Observers allowed adequate adaptation to illuminance levels in both experiments

Experimental Procedure

- Within-subjects design
- Independent variables: observer's age, ambient illuminance (Exp. 1); observer's age, element size, character color (Exp. 2)
- Dependent variables: number of incorrect display readings (mistakes), number of omissions, number of total errors (mistakes plus omissions)
- Observer's task: orally report display reading
- 371 observers, 9-78 years, 188 with normal vision (Exp. 1); 125 observers, 9-78 years, 68 with normal vision (Exp. 2)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Errors are fewer at lower ambient illuminance levels ($p < 0.01$); 12.2% errors at 48,000 lux and 23.2% errors at 80,000 lux.
- Observers over 35 years old make 20-40% more total errors ($p < 0.01$) and more omission errors ($p < 0.01$).
- The difference in errors between men and women is not statistically significant.
- Observers make fewer errors identifying red characters than green characters matched in luminance.
- Observers make fewer errors identifying characters made from the larger, dimmer elements than from smaller, brighter elements.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Recent research (Refs. 1, 3) shows that the established relationship between measured luminance and perceived brightness has been in error for self-luminous displays of high excitation purity, such as LEDs. Perceived brightness of high purity emissive sources at the spectral extremes (e.g., red and blue) are consistently underestimated by measured luminance. The red and green displays in the reported study (Ref. 2) were luminance-matched and probably had different perceived subjective brightness.

Constraints

- The red and green LED displays were of the same measured luminance and, therefore, probably had different perceived brightnesses (see Repeatability/Comparison with Other Studies).
- The generalization of these data is limited to displays of a similar excitation purity, format, and emitted luminance in high ambient illumination environments.
- Presentation rates of less than one per sec were used. Work with longer or shorter display durations might produce different results.
- It is not known if the effects would be similar with different environmental conditions.

Key References

1. Booker, R. L. (1978). Luminance-brightness comparisons of LED alphanumeric sources at the supra threshold levels. *Journal of the Optical Society of America*, *68*, 949-952.

*2. Ellis, B., & Wharf, J. (1975). The use of modern light emitting displays in the high luminance conditions of aircraft cockpits. *AGARD Conference Proceedings*, *167*, 8-1 8-11.

3. Kinney, J. A. S. (1983). Brightness of colored self-luminous displays. *Color Research and Application*, *8*, 82-89.

Table 1. Error rates for red and green displays (Exp. 2). (From Ref. 2)

	Normal Vision		All Subjects	
	E-R (%)	O-R (%)	E-R (%)	O-R (%)
Red	5.8	1.1	8.1	2.1
Green	15.9	5.6	22.7	10.4
	68 subjects		125 subjects	
	Average age 31.5 yrs		Average age 34.6 yrs	

E-R = Total error rate (mistakes and omissions)
O-R = Omission rate

Cross References

1.705 Factors affecting color discrimination and color matching;

1.710 Hue and chroma: shifts under daylight and incandescent light;

1.717 Simultaneous color contrast;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.125 Effects on instrument reading performance: pointer, background, and panel lighting colors;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue;

12.402 Transilluminated pushbutton indicators: effects of display color and ambient illumination on reaction time

Table 2. Error rates for dot-elements of different size and brightness (Exp. 2). (From Ref. 2)

	Normal Vision		All Subjects	
	E-R (%)	O-R (%)	E-R (%)	O-R (%)
Size 1 (Small bright dots)	11.4	3.8	15.7	7.1
Size 4 (Larger, dimmer dots)	7.8	2.6	11.9	4.6
	68 subjects		125 subjects	
	Average age 31.5 yrs		Average age 34.4 yrs	

E-R = Total error rate (mistakes and omissions)
O-R = Omission rate

11.124 Dial Scale Reading Times: Effects of Brightness Contrast and Color Contrast

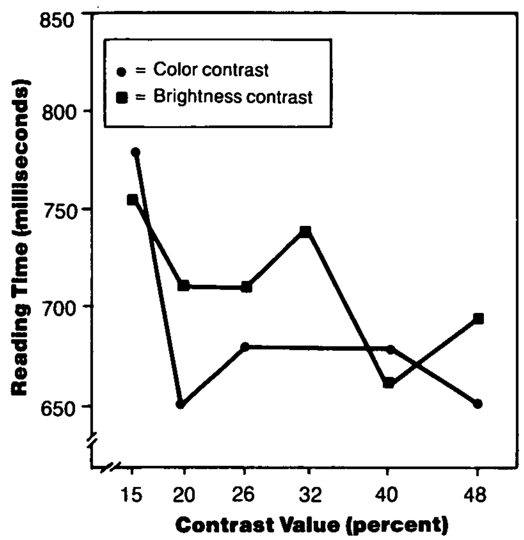


Figure 1. The effects of low to high color and brightness contrasts on reading time. (From Ref. 1)

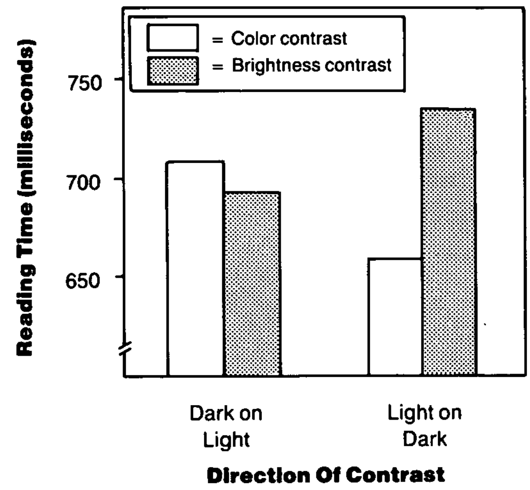


Figure 2. The effects of color and brightness contrast, as well as direction of contrast, on reading time. (From Ref. 1)

Key Terms

Color contrast; color displays; dial reading; dials; direction of contrast

General Description

Pilots and non-pilots read a series of photographs of single, circular-dial displays under different brightness contrast and color contrast conditions. Time required to read the displays decreases as the contrast value increases (Fig. 1). The addition of color contrast to a dial of a given achromatic brightness contrast decreases the time required to read the display correctly only when light symbols are presented against a darker background (Fig. 2). For dark symbols on a light background, the addition of color contrast has a negligible impact on reading times. Reading errors are not influenced by the conditions tested.

Methods

Test Conditions

- Photographs of circular dials 7.62 cm in diameter, 300 deg in length, with 50 scale units under 10 major graduations; number typeface was Futura demi-bold with stroke-width-to-height ratio of 1:5; dials displayed using tachistoscope; 45.7 cm viewing distance; average illuminance, measured at dial, 344 lux
- Half of displays (12) achromatic; made of all combinations of four grey levels ranging from 33.5-65.5% reflectance
- Half of displays (12) colored; made of all 6 combinations of yellow, blue, red, and green
- Six of each set of 12 displays had light symbols against dark background; 6 had the opposite contrast polarity
- Percent contrast = $[(B_1 - B_2)/B_1] \times 100$ where B_1 = luminance of brighter element and B_2 = luminance of dimmer element; six levels of percent contrast ranged from 14-50

Experimental Procedure

- Within-subjects design
- Independent variables: brightness contrast level, contrast condition, direction of contrast, pilots versus non-pilots
- Dependent variables: reading time, defined as time from when button pressed to illuminate dial until button release extinguished dial illumination; number of reading errors
- Observer's task: read and report dial values as quickly and accurately as possible
- 24 male observers; 12 pilots and 12 non-pilots

Experimental Results

- Averaged across contrast values, reading times are slightly but significantly shorter in the color contrast conditions than in achromatic contrast conditions ($p < 0.05$) (Fig. 1).
- The 15% color contrast condition yields significantly longer reading times than higher five color contrast conditions (20, 26, 32, 41, and 50%).
- The 14% luminance contrast condition yields significantly longer reading times only when compared to the highest luminance contrast (49%).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

- Direction of contrast interacts with the type of contrast such that light on dark contrast results in shorter reading times in the color contrast conditions, while dark on light produces highly similar reading times (Fig. 2).
- There are no significant performance differences between pilots and non-pilots.
- No significant or consistent differences are found in the analysis of errors.

Variability

No information on variability was given.

Constraints

- Although it is unlikely, different results might be found when dials are read at viewing distances other than 46 cm, or for dials of a different size.

Key References

*1. McLean, M. V. (1965). Brightness contrast, color contrast, and legibility. *Human Factors*, *7*, 521-526.

Cross References

1.717 Simultaneous color contrast;

11.123 Colored light-emitting diodes: use of red or green in high ambient illumination;

11.125 Effects on instrument reading performance: pointer, background, and panel lighting colors;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue;

11.210 Time and accuracy in reading linear scales;

11.211 Scale divisions: reading to the nearest scale mark;

11.212 Scale divisions: straight scale interpolation;

11.214 Time and accuracy in reading circular scales;

11.215 Scale divisions: reading circular dials;

11.216 Time and accuracy in reading semi-circular scales;

12.402 Transilluminated pushbutton indicators: effects of display color and ambient illumination on reaction time

11.125 Effects on Instrument Reading Performance: Pointer, Background, and Panel Lighting Colors

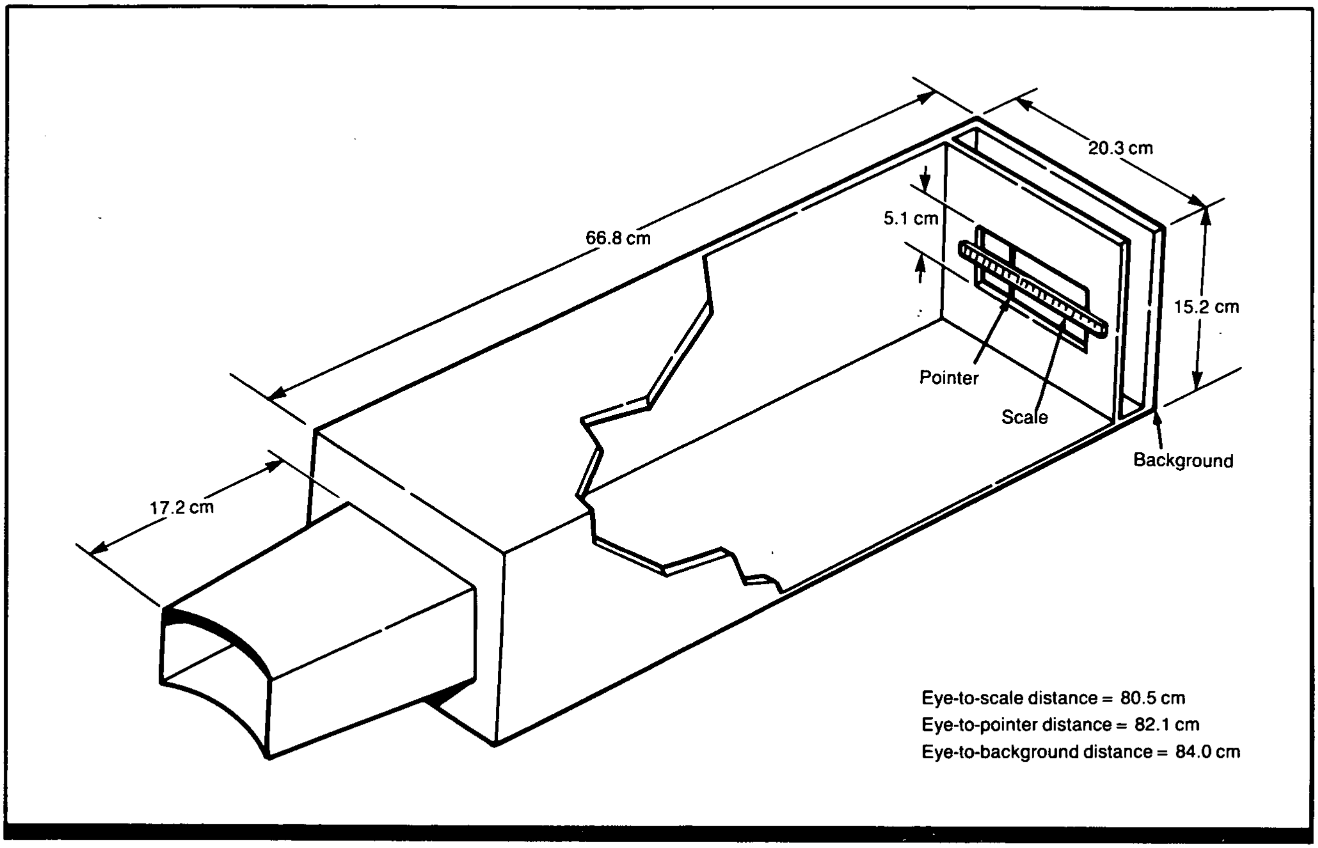


Figure 1. Presentation device. (From Ref. 1)

Key Terms

Color displays; mechanical indicators; night viewing; pointers; scales

General Description

In terms of reading accuracy, the optimum combination of pointer/background colors on a mechanical indicator display depends on the lighting system used and the level of scale illumination. An edge-lit moving pointer/fixed scale display, under two levels of illumination, both Air Force blue-white and Army/Navy red lighting systems, with all possible combinations of nine background and nine pointer/indicator colors, generates performance differences between color combinations as a function of lighting system and scale illumination level. Accuracy is very high and reasonably stable across lighting conditions for certain combinations. These are presented in the table and are expected to be suitable for both military lighting systems and at illumination levels as low as 0.03 cd/m^2.

Methods

Test Conditions

- Presentation device shown in Fig. 1; viewing time for each pointer/background combination accomplished via thyratron-controlled timer which supplied scale illumination for 0.5 sec
- Black plastic, horizontally oriented, edge-lit, moving pointer/fixed scale mechanical display; 24-point numerals, illuminated by two red-filtered bulbs; background illuminated by ten red-filtered bulbs; 0.09-cm diameter pointer/indicator mounted behind scale, movable throughout range, subtended 3 min arc of visual angle at observer's eye; background color chips mounted on shaft and moved by rotary control
- Two lighting systems: U.S. Air Force blue-white (CIE: $x = 0.440 \pm 0.02$, $y = 0.405 \pm 0.02$) and U.S. Army/Navy Instrument and Panel Lighting (IPL) red (CIE: $x = 0.705 \pm 0.015$, $y = 0.306$, $Z = 0.001$); 0.68 cd/m^2 scale luminance; two scale background luminance levels: 0.34 cd/m^2 and 0.03 cd/m^2; lighting systems (color) and levels controlled manually
- Nine pointer/indicator colors tested with nine background colors (see table for designations) were used in all possible combinations
- Ambient illumination simulated night cockpit environment
- Five self-paced trials for each experimental condition, 1620 total trials per observer; presentation order for pointer and background colors randomized across sessions; pointer positions selected from random number table

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Procedure

- Within-subjects factorial design
- Independent variables: display background color, pointer/ indicator color, panel lighting system (color), scale illumination level
- Dependent variable: percentage of reading errors
- Observer's task: state pointer/indicator position
- 42 observers, average age 21; all but one were U.S. Army enlisted men

Experimental Results

- A significant difference ($p < 0.01$) is reported between the pointer/background combinations tested.
- The optimum pointer/background color combination varies with lighting system (color) and scale illumination level; however, a very high level of accuracy (<3% errors) is exhibited for some color combinations across all lighting conditions (see Table 1).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

No similar studies were located.

Constraints

- For design purposes, consult the original study (Ref. 1) to obtain specific information.

Key References

*1. Barnes, J. A. (1971, October). What color display element. *Guidance and control displays* (AGARD-CP-96, pp. 3-1 to 3-11). Paris, France: Advisory Group for Aerospace Research and Development. (DTIC No. AD739779)

Cross References

1.722 Color specification and the CIE system of colorimetry;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.202 Redundant coding: use of color in conjunction with other codes;

11.204 Use of color coding: effect of visual field location;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue;

12.402 Transilluminated pushbutton indicators: effects of display color and ambient illumination on reaction time

Table 1. Rank of pointer/background combinations. (From Ref. 1)

Rank	Percent Error	Pointer Color	Background	Color
1	0.1	Fire Orange (Day-Glo)	Black	37038
		Blaze Orange (Day-Glo)	Black	37038
		White 37875	Black	37038
2	0.2	Saturn Yellow (Day-Glo)	Black	37038
		Yellow 13538	Black	37038
3	0.4	Arc Yellow (Day-Glo)	Grey	36231
4	0.5	Rocket Red (Day-Glo)	Black	37038
		Arc Yellow (Day-Glo)	Black	37038
		White 37875	Tan	30117
		Saturn Yellow (Day-Glo)	Tan	30117
5	0.6	White 37875	Grey	36231
		Saturn Yellow (Day-Glo)	Grey	36231
		Arc Yellow	Tan	30117
6	0.8	Fire Orange (Day-Glo)	Tan	30117
		Blaze Orange (Day-Glo	Tan	30117
7	0.9	Signal Green (Day-Glo)	Black	37038
		Yellow 13538	Grey	36231
		Yellow 13538	Tan	30117
8	1	Blaze Orange (Day-Glo)	Grey	36231
		Saturn Yellow (Day-Glo)	Blue	35299
9	2	Rocket Red (Day-Glo)	Grey	36231
		Fire Orange	Grey	36231
		White 37875	Grey	36373
		White 37875	Blue	35299
		Rocket Red (Day-Glo)	Tan	30117
10	3	Arc Yellow (Day-Glo)	Blue	35299
		Yellow 13538	Blue	35299

11.126 Color Misregistration: Effect on Symbol Identification

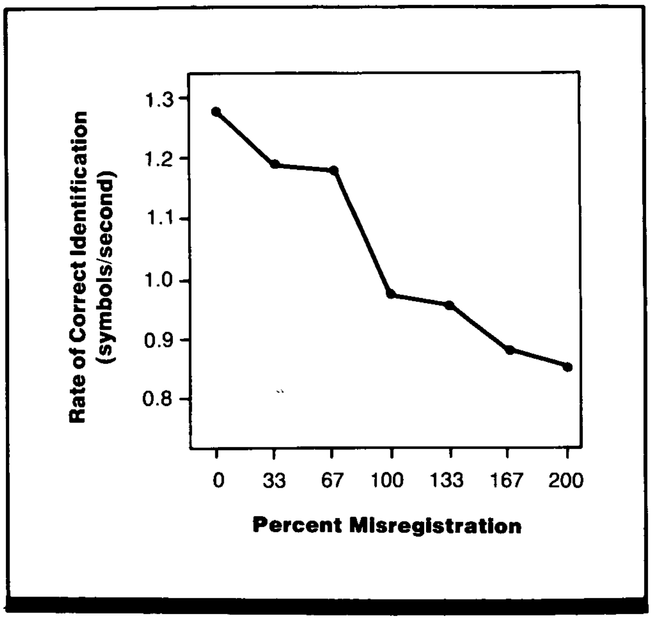


Figure 1. Performance as a function of misregistration. (From Ref. 2)

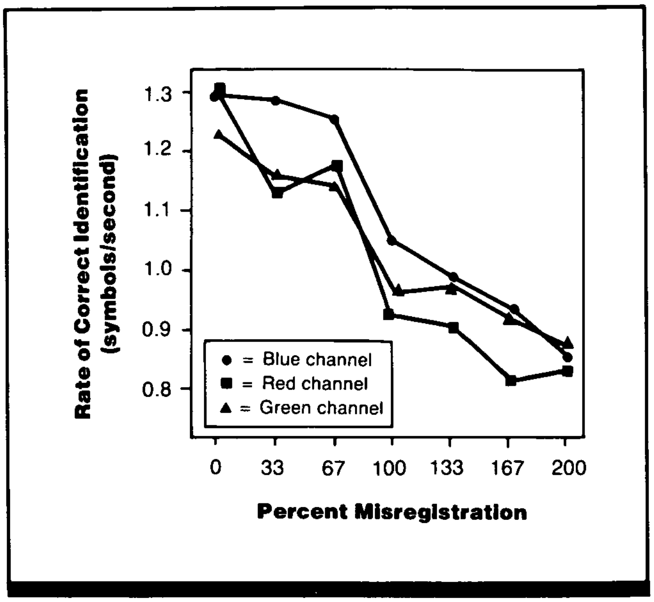


Figure 2. Performance as a function of primary channel misalignment and misregistration. (From Ref. 2)

Key Terms

Alphanumeric displays; color additive displays; color coding; color registration; CRT displays; information display; information portrayal; symbol identification

General Description

Misregistration of colors in alphanumeric displays affects symbol identification. It typically occurs when two spots of primary colors projected to the same position on a display surface to form a secondary color do not have their edges exactly aligned. Performance grows progressively worse as misregistration increases from 0-200%, but the decrement does not reach significant levels until 100% misregistration. The best performance is attained with red and blue symbols at every level of misregistration, while the poorest performance is attained with cyan (greenish-blue) and white symbols.

Methods

Test Conditions

- Misregistration defined as $100(M-S)/S$ where M is stroke width of misregistered symbol and S is stroke width of perfectly registered symbol; misregistration levels of 0, 33, 67, 100, 133, 167, and 200% were used
- Three-channel color-additive projector (Colorvision, 2.2 KW Hanovia Xenon-light source) and 70-mm filmstrip with three fields; dichroic filters separated light source into red, blue, and green primaries, which were individually projected onto screen
- Symbol matrices generated on Charactron tube, photographed on Kalvar 70-mm film; each matrix contained alphanumeric symbols in red, green, blue, magenta, yellow, cyan, and white; each matrix contained a different set of randomly generated sequence of symbols, in 18 x 14 format; capital letters and digits (0-9) used; font style from Strategic Air Command control system group display
- Symbol brightness varied with color, from 10.2 cd/m^2 for blue to 113.0 cd/m^2 for white; background brightness was 1.7 cd/m^2
- Observer seated 5.64 m from screen; symbol height was 4.4 cm, 27 min arc of visual angle subtended at observer's eye
- Solenoid-operated shutter controlled exposure and automatic timer measured observer's exposure time
- Twenty-one trials per day, 7 days total; one misregistration level tested each day with three primary channels and seven symbol colors

Experimental Procedure

- Split plot (mixed) design
- Independent variables: presentation order (ascending or descending registration order); degree of misregistration; primary channel misalignment; symbol color
- Dependent variables: number of correct symbols identified per sec for each trial
- Observer's task: read symbols only of a specified color on each trial, perform as quickly and accurately as possible, scanning from left to right
- 6 male, college-age observers with 20/20 corrected or uncorrected visual acuity and normal color vision

Experimental Results

- Presentation order is not significant; there is a significant interaction ($p < 0.01$) between presentation order and misregistration level, with an improvement in performance (except at 200% misregistration) as registration improves.
- Misregistration has a significant effect ($p < 0.01$) on performance. Performance level decreases as misregistration increases from 0-200%.
- Primary channel misalignment has a significant effect ($p < 0.01$) on performance and there is a significant inter-

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action ($p < 0.05$) between misalignment and misregistration level. In general, performance is poorest with red or green channel misalignment; however, there is considerable variation within misregistration levels.

- Performance is significantly better with red and blue symbols and significantly poorer with white and cyan symbols ($p < 0.01$).
- There is a significant interaction ($p < 0.01$) between misregistration level, primary channel misalignment, and symbol color, due to performance variations for each symbol color under each level of misregistration for all three conditions of primary channel misalignment.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

No other studies of colored alphanumeric misregistration are known. In an earlier study (Ref. 1) of color identification of simple geometric forms, performance was relatively constant for 0-65% misregistration. However, response times became progressivley slower for greater misregistration.

Constraints

- Simulated electronic displays were used. Experience with smaller character sizes and actual displays suggests that misregistration should be minimized.
- Neither specific color coordinates nor wavelength compositions were stated.
- Primary channel misalignment order, and color symbol reading order were not randomized (authors state that preliminary studies had shown no order effect for these variables).
- Luminance levels were not equalized across colors. However, in applications with filtered lamps, luminances would not be equal.
- Only horizontal misregistration was tested.

Key References

1. Snadowsky, A. M., Rizy, E. F., & Elias, M. F. (1964). *Misregistration in color additive displays* (RADC-TDR-64-488). Rome Air Force Base, NY: Rome Air Development Center, Air Force Systems Command. (DTIC No. AD610528)

*2. Snadowsky, A. M., Rizy, E. F., & Elias, M. F. (1966). Symbol identification as a function of misregistration in color additive displays. *Perceptual and Motor Skills, 22*, 951-960.

Cross References

7.513 Search time: effect of number of colors and information density;

11.109 CRT symbol size, viewing angle, and vertical resolution: effect on identification accuracy;

11.111 CRT symbol size and resolution: effect on legibility;

11.112 CRT symbol size and stroke width: effect on legibility;

11.113 CRT symbol spacing: effect on identification accuracy;

11.209 Alphanumeric font and display legibility

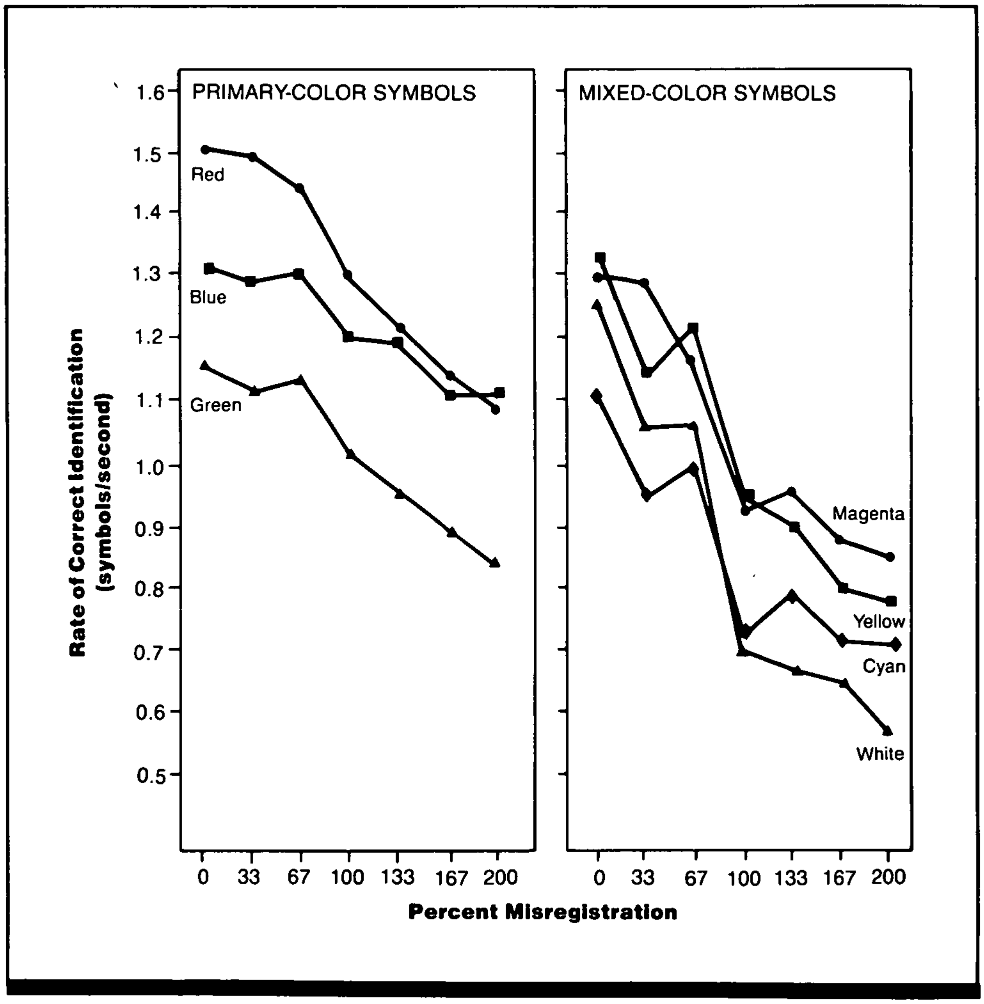

Figure 3. Performance as a function of misregistration and symbol color. (From Ref. 2)

11.201 Color-Coded Versus Monochrome Displays

Table 1. Summary of selected recent CRT display color-coding research.

Source	Task and Results
CRefs. 7.513, 7.519	Detect out-of-tolerance conditions in static simulation of electronically generated cockpit displays while doing a tracking task. Color as a cue resulted in best performance (combined measure of tracking accuracy and detection speed). Color with no meaning yielded poorest performance. Benefits of color as a cue most apparent with more difficult tracking tasks
Ref. 5	Recognize threats on a cathrode ray tube (CRT) display while performing other flight-related tasks. Densely packed threat symbols either shape-coded only or redundantly color-coded. Redundant color coding significantly reduced both response time and error rate
Ref. 1	Perform stores-management tasks while flying aircraft simulator. Monochrome alphanumeric, color pictorial, alphanumeric/color pictorial, and monochrome pictorial threat displays compared. Response times significantly higher for monochrome pictorial format. Errors significantly lower for monochrome alphanumeric color pictorial format
Ref. 7	Respond to questions about aircraft fuel system status while performing a secondary tracking task. Fuel system displays either monochrome pictorial or color pictorial. Redundant color coding improved search performance, but not identification performance
Ref. 3	Report aircraft engine system failures and parameter values while flying aircraft simulator. Engine information presented using conventional eletromechanical, monochrome CRT, or color CRT displays. No significant differences between color and monochrome CRT formats, but both better than conventional instruments. Lack of color-coding value attributed to display simplicity and adequacy of shape coding
Ref. 9	Perform computer-aided decision-making task; telephone line-testing system. Four CRT formats compared: narrative text, structured text, monochrome graphics, color graphics. Accuracy unaffected by format. Response times significantly shorter for either graphic format. Display color did not affect performance. Subjects preferred color graphics format

Key Terms

Coding; color coding; CRT displays; display density; information portrayal; TV displays; visual search

General Description

Color coding of displays can sometimes improve visual search and identification performance over monochrome formats. The impact of color coding is highly situation-specific and depends on factors such as operator task, display format and density, and work environment (Ref. 6). For highly dense displays with a visual search requirement, color coding provides performance enhancement not available with other coding methods. However, task-irrelevant use of color, or using seven or more colors in computer-generated displays, can cause performance decrements (Ref. 2). Color coding (Ref. 6) should improve operator performance when: (1) display is unformatted, (2) symbol density is high, (3) operator must search for relevant information, (4) symbol legibility is degraded, or (5) color codes are logically related to operator tasks. Recent research supports these guidelines. There is also some evidence (CRefs. 7.513, 7.519) that color coding may improve visual search and identification performance when task loading is high. Operator preference strongly favors color displays.

Applications

The design of electronically generated color-coded displays.

Constraints

- In the research cited, monochrome displays differed from their color counterparts in more ways than just the absence of color.
- There are no standard metrics of display density, extent of display formatting, or operator task loading. Thus, mission-critical expectations of operator performance enhancements from display color coding should be empirically verified.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Aretz, A. J., & Calhoun, G. L. (1982). Computer-generated pictorial stores management displays for fighter aircraft. *Proceedings of the Human Factors Society 26th Annual Meeting* (pp. 455-459). Seattle, WA: Human Factors Society.

2. Cahile, M., & Carter, R. C., Jr. (1976). Color code size for searching displays of different density. *Human Factors, 18*, 273-280.

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5. Kopala, C. J. (1979). The use of color-coded symbols in a highly dense situation display. *Proceedings of the Human Factors Society 23rd Annual Meeting* (pp. 397-401). Boston, MA: Human Factors Society.

6. Krebs, M. J., Wolf, J. D., & Sandvig, J. H. (1978, October). *Color display design guide* (ONR-CR213-136-2F). Arlington, VA: Office of Naval Research. (DTIC No. ADA066630)

7. Lunder, C. B., & Barber, P. J. (1984, February). Redundant color coding on airborne CRT displays. *Human Factors, 26*, 19-32.

8. Reising, J. M., & Calhoun, G. L. (1982). Color display formats in the cockpit: Who needs them? *Proceedings of the Human Factors Society 26th Annual Meeting* (pp. 446-449). Seattle, WA: Human Factors Society.

9. Tullis, T. S. (1981). An evaluation of alphanumeric, graphic and color information displays. *Human Factors, 23*, 541-550.

Cross References

7.513 Search time: effect of number of colors and information density;

7.519 Search time: effect of color coding;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.202 Redundant coding: use of color in conjunction with other codes;

11.203 Use of color coding: effect of display density;

11.204 Use of color coding: effect of visual field location;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue

11.202 Redundant Coding: Use of Color in Conjunction with Other Codes

Table 1. Summary of selected research on redundant color coding.

Source	Task	Redundant Codes	Results
Ref. 7	Visual search, counting	Color, alphanumerics	Redundant color coding significantly reduces search time, counting time, and counting errors
Ref. 1	Monitoring	Color, digits	No significant differences in performance when redundant coding was used
Ref. 6	Visual search	Color, alphanumerics	Redundant color coding significantly reduces search time for locating information on maps
Ref. 5	Visual search	Color, geometric shapes	Color alone and redundant color/shape coding both produce significantly shorter response times than shape alone No significant differences in response times between color alone and color/shape coding
Ref. 2	Visual search, counting, identification	Color, symbols	Redundant color coding significantly reduces response times and error rates The magnitude of the benefit from redundant color coding is more pronounced at higher display information density levels
Ref. 3	Visual search, counting, comparing	Color, symbols	Redundant color coding significantly reduces response times and significantly reduces error rates at higher display densities The benefit of redundant color coding increases with display density increases

Key Terms

Coding; color coding; information portrayal; redundant coding; symbol coding

General Description

In redundant symbol coding, two or more codes are combined so that one coding dimension conveys information also available from another dimension. Redundant coding may be either complete or partial. With complete redundancy, the information conveyed by each code is completely duplicated. For example, color and alphanumeric coding could be combined by having each of nine digits identified by a different color. Then, knowing the color of a symbol would automatically establish its alphanumeric value. With partial redundancy, the information match between codes is not perfect; knowledge of one coding dimension gives only an approximation of the value of the other dimension. Using the earlier example of color and alphanumeric codes, each color might be associated with a range of values. For example, knowing the color of a target might specify only the subset of digits to which it belongs. As a second example, red may indicate any one of several values, all in the danger zone of values.

The table summarizes six studies on the topic of redundant color coding. Redundant color coding often results in significantly improved performance. The performance benefits are most likely to result when color is used to aid in visual search or draw attention to a specific item of information.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Totally redundant color coding may be used in the design of displays where symbols may be difficult to discriminate because of visual noise ("snow"), poor luminance contrast, or when targets may be difficult to locate because of display clutter. In displays of terrain, for example objects are often not discriminable by the equipment itself, so that they cannot be color coded for an observer. Partially redundant coding may be useful where both general and specific status information is meaningful at different times.

Constraints

- Color should be added to a display only when color has a direct bearing on the operator's task; otherwise, color will not benefit performance and may even degrade it.

Key References

1. Kanarick, A. F., & Petersen, R. C. (1971). Redundant color coding and keeping-track performance. *Human Factors, 13*, 183-188.

2. Kopala, C. J. (1979). The use of color coded symbols in a highly dense situation display. *Proceedings of the Human Factors Society 23rd Annual Meeting* (pp. 397-401). Boston, MA: Human Factors Society.

3. Kopala, C. J., Calhoun, G. L., & Herron, E. L. (1983, January). *Symbol verification study* (AFWAL-TR-82-3080). Wright-Patterson AFB, OH: Air Force Wright Aeronautical Laboratory. (DTIC No. ADA131328)

4. Krebs, M. J., Wolf, J. D., & Sandvig, J. H. (1978, October). *Color display design guide* (ONR-CR213-136-2F). Arlington, VA: Office of Naval Research. (DTIC No. ADA066630)

5. Saenz, N. E., & Riche, J. R. (1974). Shape and color as dimensions of a visual redundant code. *Human Factors, 16*, 308-313.

6. Shontz, W. D., Trumm, G. A., & Williams, L. G. (1971). Color coding for information location. *Human Factors, 13*, 237-246.

7. Smith, S. L. (1963). Color coding and visual separability in information displays. *Journal of Applied Psychology, 47*, 358-364.

Cross References

7.513 Search time: effect of number of colors and information density;

7.519 Search time: effect of color coding;

11.203 Use of color coding: effect of display density;

11.204 Use of color coding: effect of visual field location;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue;

11.206 Color coding: compatible and non-compatible control/display arrangements

11.203 Use of Color Coding: Effect of Display Density

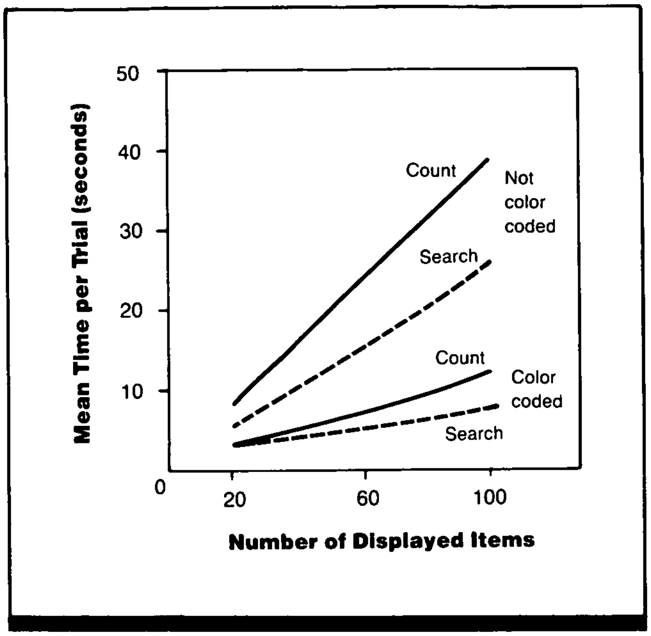

Figure 1. Counting and search times as a function of display density and color coding. (From Ref. 4)

Figure 2. Counting errors as a function of display density and color coding. (From Ref. 4)

Key Terms

Coding; color coding; color displays; information density; information display; redundant coding; search time; shape coding

General Description

Display density refers to the number of symbols presented in a display. What benefit does color coding of information have as a function of display density? Three aspects of the question are examined: (1) when color is added to a display to redundantly code information, (2) when color is compared to other coding methods, and (3) when time constraints are placed on viewing time.

When the task is to identify items of a common class and display information density is low, redundant color coding has only a small effect on performance (Figs. 1, 2). The benefit of color coding increases with display density. Other studies have found similar results (Refs. 1, 2).

A comparison of color-coding and various shape-coding strategies is shown in Figs. 3 and 4. Again, color coding is most effective at higher display densities, offering only a slight performance advantage over the other methods at low density levels. A related study (Ref. 5) compared symbolic, numeric, and color coding, and reported similar results.

Figure 5 illustrates performance effects when viewing time is constrained. Note that color coding is advantageous at all display densities and exposure times tested.

The general conclusion from these studies is that the performance benefits in both speed and accuracy from color coding increase with display information density.

Applications

Designing high information density displays; color coding is particularly effective for grouping related items and classifying symbols for search-type tasks.

Constraints

- Color coding improves performance in high-density displays only when the target color is known; otherwise, it may degrade performance by acting as a distractor. If the equipment does not automatically discriminate targets from other objects, it cannot color code them.
- There are no standard metrics of display density. Thus the benefit of color may require empirical verification.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

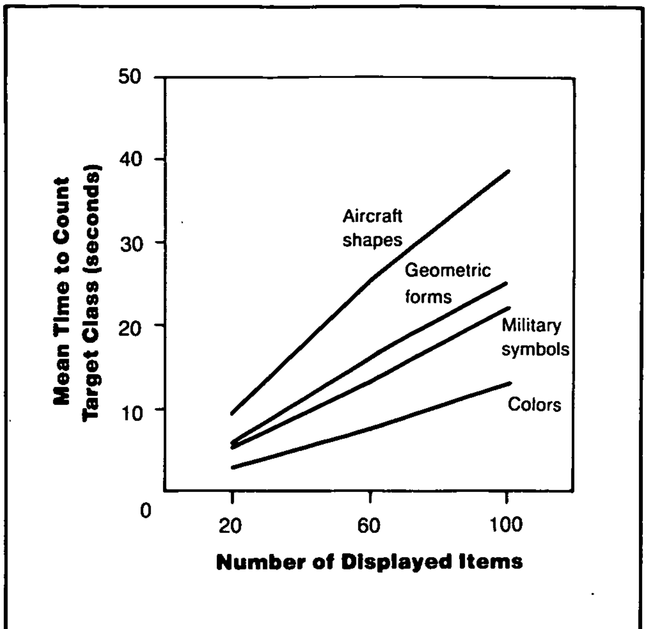

Figure 3. Counting times as a function of display density and coding methods. (From Ref. 6)

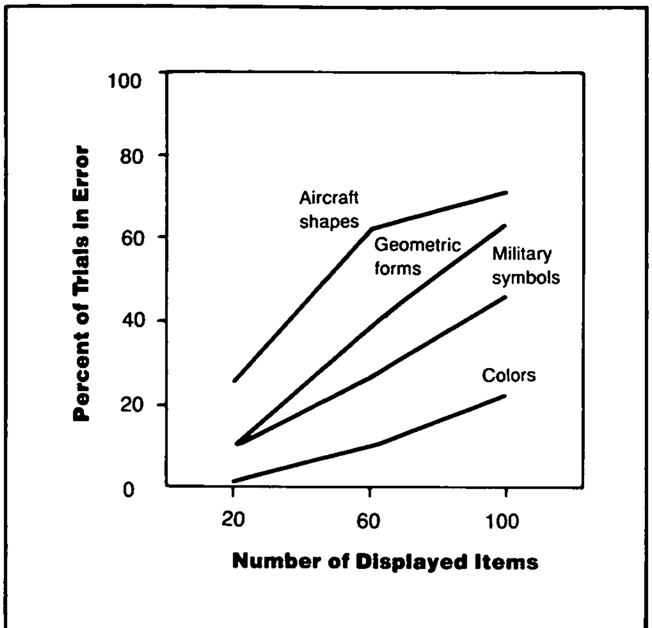

Figure 4. Counting errors as a function of display density and coding methods. (From Ref. 6)

Key References

1. Kopala, C. J. (1979). The use of color-coded symbols in a highly dense situation display. *Proceedings of the Human Factors Society 23rd Annual Meeting* (pp. 397-401). Boston, MA: Human Factors Society.

2. Kopala, C. J. (1983, January). *Symbology verification study* (AFWAL-TR-82-3080). Wright-Patterson AFB, OH: Flight Dynamics Laboratory. (DTIC No. AD131328)

*3. Krebs, M. J., Wolf, J. D., & Sandvig, J. (1978, October). *Color display design guide* (ONR-CR213-136-2F). Arlington, VA: Office of Naval Research. (DTIC No. ADA066630)

*4. Smith, S. L. (1963). Color coding and visual separability in information displays. *Journal of Applied Psychology, 47*, 358-364.

5. Smith, S. L., Farquhar, B. B., & Thomas, D. W. (1965). Color coding in formatted displays. *Journal of Applied Psychology, 49*, 393-398.

*6. Smith, S. L., & Thomas, D. W. (1964). Color versus shape coding in information displays. *Journal of Applied Psychology, 48*, 137-146.

Cross References

7.513 Search time: effect of number of colors and information density;

7.519 Search time: effect of color coding;

11.123 Colored light-emitting diodes: use of red or green in high ambient illumination;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.201 Color-coded versus monochrome displays;

11.202 Redundant coding: use of color in conjunction with other codes;

11.204 Use of color coding: effect of visual field location;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue;

11.206 Color coding: compatible and non-compatible control/display arrangements

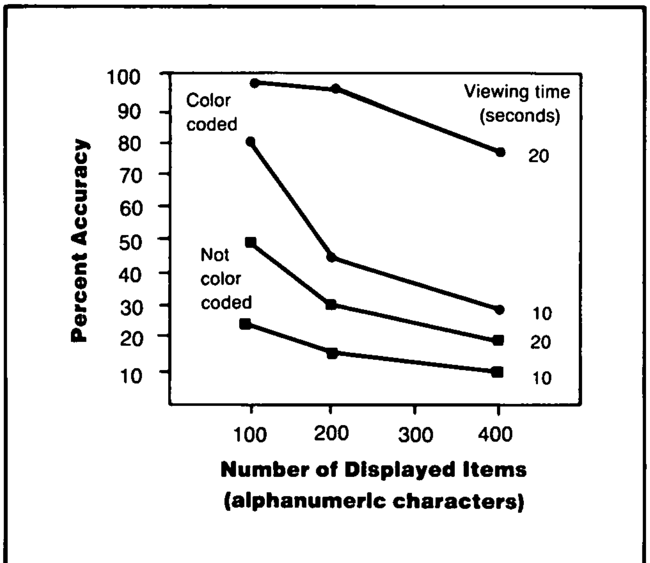

Figure 5. Accuracy of locating targets as a function of display density and exposure time. (From Ref. 3)

11.204 Use of Color Coding: Effect of Visual Field Location

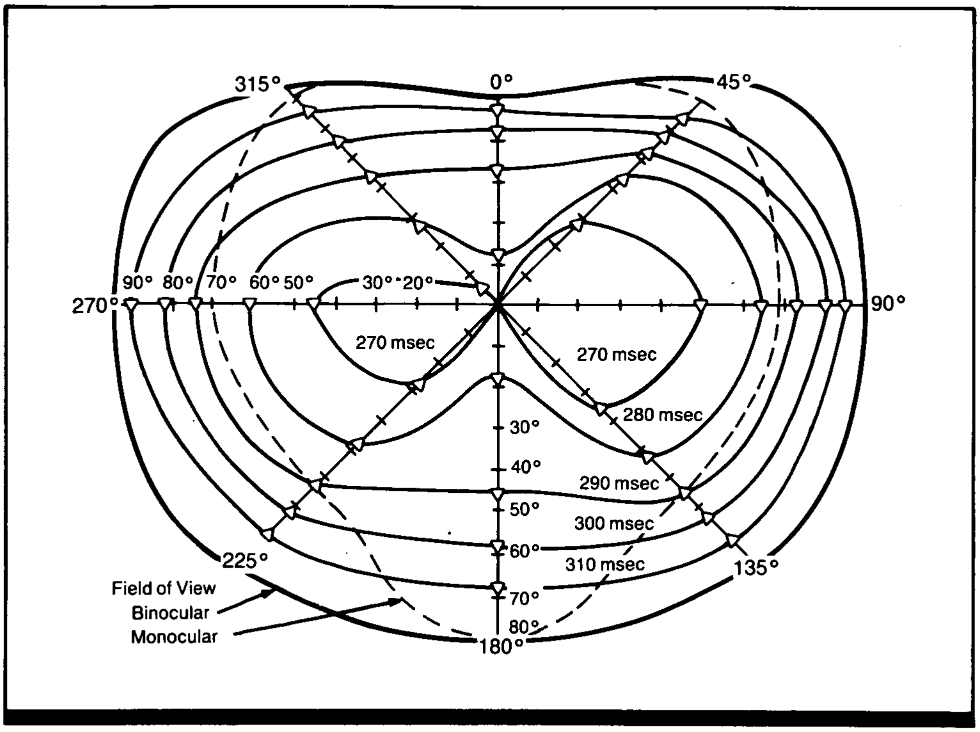

Figure 1. Retinal iso-response time zones for white stimuli. (From Ref. 2)

Key Terms

Coding; color coding; field of view; information portrayal; peripheral vision; reaction time

General Description

Response times to colored stimuli depend upon their location in the visual field. The widest field of view and shortest response times are for white stimuli, while the narrowest field of view and the longest response times are for red. Values for blue, green, and yellow differ very little from one another in terms of these variables and are intermediate between white and red. The visual field has relatively concentric oval regions corresponding to each color, within which response times can be expected to be approximately equal. The regions are centered near the fovea and extend outward, farther horizontally than vertically. Regardless of stimulus color, detection is worst within a 40-80 deg arc of visual angle below the fovea, and best within a 30-deg arc from the center of fovea. Peripheral vision is poor for detecting targets, especially if they are small or stationary.

Methods

Test Conditions

- 18 stimulus sources: light from fluorescent, cold, cathode flash tube (G.E. F4T5-CW, 1- sec rise time); projected through fiber optic bundle and an 8-mm diameter (45-min arc of visual angle diameter) hemispheric lens mounted on black metal arc; 10-deg arc separations from 0-80 deg arc on one side to 0-90 deg arc on the other side of the fovea (0 deg-angle) along given meridian between observer's line of sight and stimulus position; meridian locations (with respect to fovea): 0, 45, 90, 135, 180, 225, 270, or 315 deg; stimulus duration of 50 msec
- Red, green, blue, and yellow stimulus color produced by chromatic and neutral density filters placed between flash tube and fiber optic bundle; luminances of blue, yellow, and green (but not red, due to filter limitations) stimulus were of equal low luminance, but easily visible when viewed directly
- Supine observer: eyes directly below and 0.61 m from fixation point of yellow-green fluorescent tape cross, broken at center by 1 deg 19 min arc angular separation (for placement of 0-0 deg stimulus), arms of cross subtended 17 min arc width and 8 deg 27 min arc length, just foveally visible by observer's adjustment of ultraviolet projector
- Observers trained with white stimulus until mean response times reached asymptotic levels (6-7 days)
- Observers dark-adapted for 15 min prior to each test session

Experimental Procedure

- Repeated measures
- Independent variables: stimulus position, meridian, and color; observer's sex
- Dependent variables: response time (elapsed time from presentation of stimulus until observer pressed response button); frequency of no-responses (defined as failure of observer to respond within 1800 msec of stimulus presentation)
- Observer's task: press spring-loaded button when light stimulus observed
- 7 observers, 4 male and 3 female, ages 18-34, with normal visual acuity (20/20) and normal color vision

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Figure 1 shows response times (RT) for white stimuli plotted as iso-RT zones within the full visual field. The contour lines indicate similar response times to stimuli.
- The data from white, blue, yellow, green, and red stimuli are summarized in Fig. 2. The widest field of view and the shortest response times over the entire field of view are for white stimuli, while the narrowest field of view and the longest response times are for red. Green, blue, and yellow yield quite similar fields of view and response times, and fall between red and white.
- Considering only no-response (NR) data for blue, yellow, and green, the results indicate: the lowest percentage of NRs occurs within the ± 30 deg range vertically from the fovea (1.4%), while the highest percentage of NRs occurs within the 40-deg region below the fovea (7%); the 0-50 deg region above the fovea yields 6% NRs; across the horizontal median, the lowest percentage (1.1%) of NRs occurs within the 40-80 deg left region, while the highest percentage (2.8%) occurs within the 0-30 deg right region. The 40-90 deg right region yields 1.9% NRs.

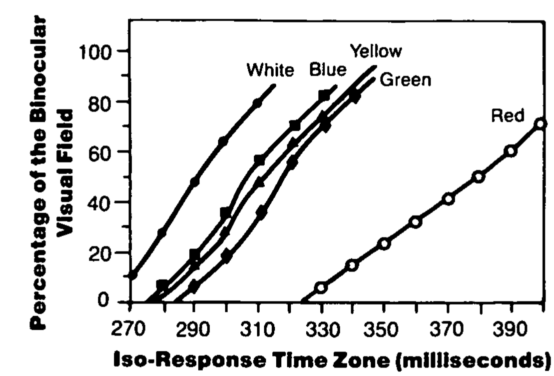

Figure 2. Percentage of binocular visual field represented by iso-response time zones for white, blue, yellow, green, and red stimuli. (From Ref. 2)

Repeatability/Comparison with Other Studies

Results compare well with a previous study (Ref. 3) from the same laboratory. Relatively close agreement is also found with Refs. 4 and 5, taking into account differences in stimulus luminance, dominant wavelength, and number of stimuli presented. Somewhat discrepant findings are reported in Ref. 1.

Constraints

- Response time (RT) data were obtained under almost ideal viewing conditions. Caution should be exercised in applying data to situations where observer is light-adapted, continually fixating new locations, uncertain about stimulus onset or location, fatigued, etc.
- The stimulus luminance level was well below that recommended for warning, caution, and advisory light-indicators for night-viewing conditions. Response times are likely to be shorter for higher luminance levels.
- Non-availability of neutral density filters in log steps below 0.1 makes it impossible to match red to the other three colors (green, blue, and yellow). Therefore, performance differences may be due, in part, to the lower luminance (1.6 $\log_{10}$ units dimmer) level of red.

Key References

1. Dudek, R. A., & Colton, G. M. (1970). Effects of lighting and background with common signal lights on human peripheral color vision. *Human Factors, 12,* 401-407.

*2. Haines, R. F., Dawson, L. M., Galvan, T., & Reid, L. M. (1975, March). *Response time to colored stimuli in the full visual field* (NASA-TN-D-7927). Moffett Field, CA: NASA Ames Research Center.

3. Haines, R. F., Gross, M. M., Nylen, D., & Dawson, L. M. (1974, June). *Peripheral visual response time to colored stimuli imaged on the horizontal meridian* (NASA-TM-X-3086). Moffett Field, CA: NASA Ames Research Center.

4. Lit, A., Young, R. H., & Shaffer, M. (1971). Simple reaction time as a function of luminance for various wavelengths. *Perception & Psychophysics, 10,* 397-399.

5. Pollack, J. D. (1968). Reaction time to different wavelengths at various luminances. *Perception & Psychophysics, 3,* 17-27.

Cross References

1.237 Normal visual fields for color;

7.513 Search time: effect of number of colors and information density;

7.519 Search time: effect of color coding;

11.123 Color light-emitting diodes: use of red or green in high ambient illumination;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.201 Color-coded versus monochrome displays;

11.202 Redundant coding: use of color in conjunction with other codes;

11.203 Use of color coding: effect of display density;

11.206 Color coding: compatible and non-compatible control/display arrangements

11.205 Use of Color Coding: Effect of Symbol Luminance, Illumination Level, and Hue

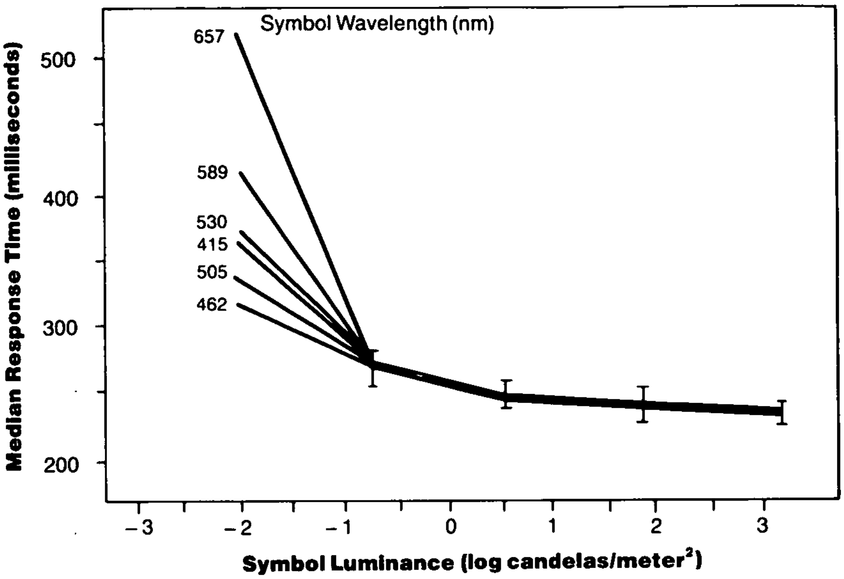

Figure 1. Median response time in milliseconds as a function of symbol luminance for six symbol wavelengths (brackets indicate 0.01 confidence interval). (From Ref. 1)

Key Terms

Coding; color coding; color displays; information portrayal; reaction time; symbol luminance

General Description

Several factors must be considered when determining a suitable color coding set for a particular application. Ambient illumination, symbol luminance, and symbol color interact. At low levels of ambient illumination, symbol luminance must be reduced to maintain dark adaptation, but if reduced to <3 cd/m^2, colors cannot be reliably differentiated. At high levels of ambient illumination, symbol luminance must be significantly increased to compensate for the apparent color fading or washout that can occur due to the reduction in the symbol-to-background contrast. Also, performance with specific wavelengths (colors) is not uniformly affected by ambient illumination. Figure 1 illustrates the effect of symbol luminance and wavelength on response time at low ambient illumination. At lower luminance levels, response times are shorter to wavelengths in the blue-to-green region of the spectrum. Figure 2 illustrates the effect of symbol wavelength and luminance on response time under high levels of ambient illumination (10^5 lux). Response time is longer for targets in the yellow region of the spectrum, while in the red and blue regions response time is much less affected by symbol luminance. This differential effect for wavelength is further illustrated in Figure 3. With high ambient illumination (e.g., 10^5 lux), response to red targets is faster than for either green or yellow targets at all levels of symbol luminance. It is apparent that the entire range of ambient lighting conditions must be taken into consideration when determining a suitable color-coding set and the required luminance levels for a specific application.

Applications

The selection of a color-coding set where dark adaptation may be required or color washout may be a problem.

Constraints

- Both the intensity and color of environmental lighting should be considered when choosing a color-coding set, since colored ambient light may alter colors and color perception, particularly for surface colors.
- Luminance ratios required for adequate reaction times are affected by both symbol size and the number of colors used.

Key References

*1. Krebs, M. J., Wolf, J. D., & Sandvig, J. H. (1978, October). *Color display design guide* (ONR-CR213-136-2F). Arlington, Va: Office of Naval Research. (DTIC No. ADA066630)

2. Pollack, J. D. (1986). Reaction time to different wavelengths at various luminances. *Perception & Psychophysics, 3*, 17-24.

3. Semple, C. A., Jr., Heapy, R. J., Conway, E. J., & Burnette, K. Y. (1971, April). *Analysis of human factors data for electronic flight display systems* (AFFDL-TR-70- 174). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory. (DTIC No. AD884770)

4. Tyte, R., Wharf, J., & Ellis, B. (1975). Visual response times in high ambient illumination. *Society of Information Display Digest*, 98-99.

Cross References

7.513 Search time: effect of number of colors and information density;

7.519 Search time: effect of color coding;

11.123 Color light-emitting diodes: use of red or green in high ambient illumination;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.201 Color-coded versus monochrome displays;

11.202 Redundant coding: use of color in conjunction with other codes;

11.203 Use of color coding: effect of display density;

11.204 Use of color coding: effect of visual field location;

11.206 Color coding: compatible and noncompatible control/display arrangements

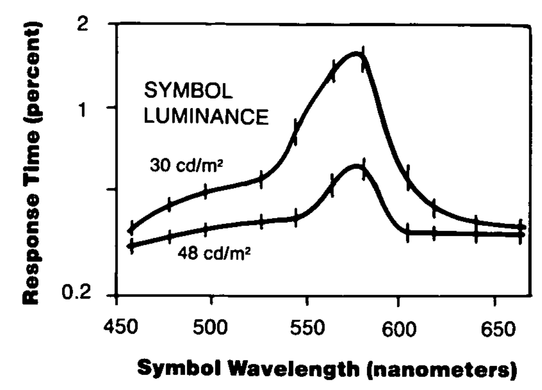

Figure 2. Response time as a function of wavelength for ambient illumination of 10^5 lux. (From Ref. 1)

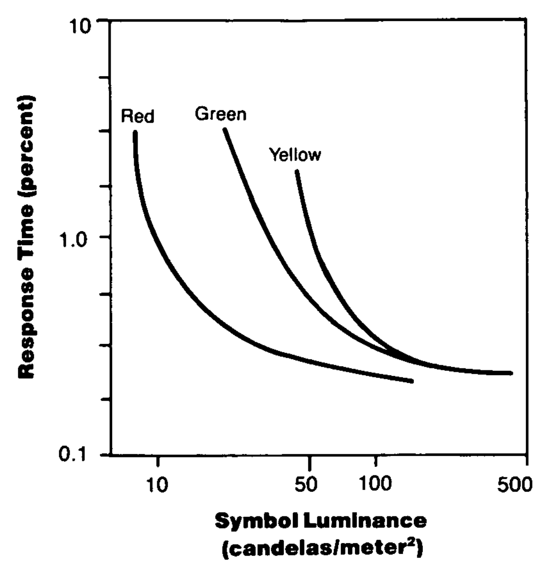

Figure 3. Response time as a function of symbol luminance. (From Ref. 1)

11.206 Color Coding: Compatible and Non-Compatible Control/Display Arrangements

Key Terms

Color coding; color displays; control/display compatibility; information portrayal; reaction time; toggle switches

General Description

Color coding can have a marked effect on performance with non-compatible control/display (C/D) arrangements. Controls should generally be below or to the right of their associated displays. When associated controls and displays are located so that their relationship is not obvious (positional non-compatibility), confusion results. Response times for observers to extinguish a light with the associated toggle switch varies with the compatibility of the C/D arrangement and the presence or absence of color coding. Response time for compatible C/D arrangements is significantly faster than for non-compatible arrangements. Color coding of lights and toggle switches does not improve performance on compatible arrangements, but can significantly improve performance on non-compatible arrangements. However, performance with color-coded non-compatible arrangements still does not match performance with compatible arrangements.

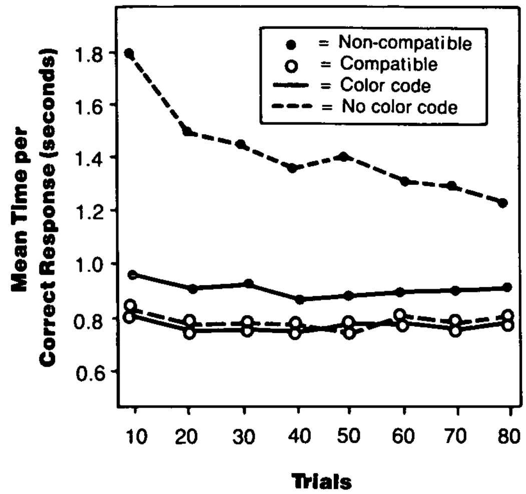

Figure 1. Average time to make correct responses. (From Ref. 2)

Methods

Test Conditions

- Four test panels, each 30 x 61 cm
- Color-coded panels; red, green, blue, and white lights in 2 x 2 matrix on upper half of panel; color match indicates associated controls and displays
- Non-color-coded panels: same matrix layout, but all lights red and all toggles white
- Compatible panels: Controls and displays in corresponding locations (e.g., upper right control associated with upper right display, etc.)
- Non-compatible panels: positions of associated controls and displays do not correspond (e.g., upper-right control might be associated with lower-left display, etc.) and must be learned by trial and error
- Apparatus explained and demonstrated: observer given 12 practice trials before start of test runs; each light illuminated randomly an equal number of times in each half of test run

Experimental Procedure

- Completely randomized between-subjects factorial design
- Independent variables: compatible or non-compatible C/D positional relationship; color-coded or non-color-coded C/D relationship
- Dependent variable: correct response time, defined as the time interval between light onset and observer turning it off
- Observer's task: move hand from black marker at bottom of test panel and throw associated toggle switch to extinguish light
- 40 subjects, 10 per group, Army, Navy, and Marine male officers with normal color vision

Experimental Results

- There is a significant difference ($p < 0.005$) between the first and last half of the 80 trials, indicating a practice effect; therefore, data presented here are for the last 40 trials only.
- There are significant effects ($p < 0.001$) for panel compatibility, panel color coding, and the interaction between them.
- Color coding improves response time for the non-compatible arrangement by 40-50% ($p < 0.05$).
- Color coding has no significant effect on response time for the compatible arrangement.
- Response times with both compatible arrangements are significantly shorter ($p < 0.05$) than those with non-compatible arrangements for either color coding condition.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Performance data are similar to that obtained by Chapanis and Lockhead (Ref. 1) who compared compatible and non-compatible arrangements with or without lines connecting associated controls and displays. The earlier study showed that most of the effect was attributable to the compatibility factor.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Because best performance is found with the compatible C/D arrangements, designers should strive to achieve compatibility and only resort to color coding where C/D compatibility is not feasible.
- Results of present study apply only to white light ambient illumination.

Key References

1. Chapanis, A., Lockhead, G. R. (1965). A test of the effectiveness of sensor lines showing between displays and controls. *Human Factors, 7*, 219-230.

*2. Poock, G. K. (1969). Color coding effects in compatible and noncompatible display-control arrangements. *Journal of Applied Psychology, 53*, 301-303.

Cross References

7.513 Search time: effect of number of colors and information density;

7.519 Search time: effect of color coding;

9.110 Factors affecting choice reaction time;

11.201 Color-coded versus monochrome displays;

11.202 Redundant coding: use of color in conjunction with other codes;

11.203 Use of color coding: effect of display density;

11.204 Use of color coding: effect of visual field location;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue

11.207 Display Element Shape: Effect on Reading and Search Times

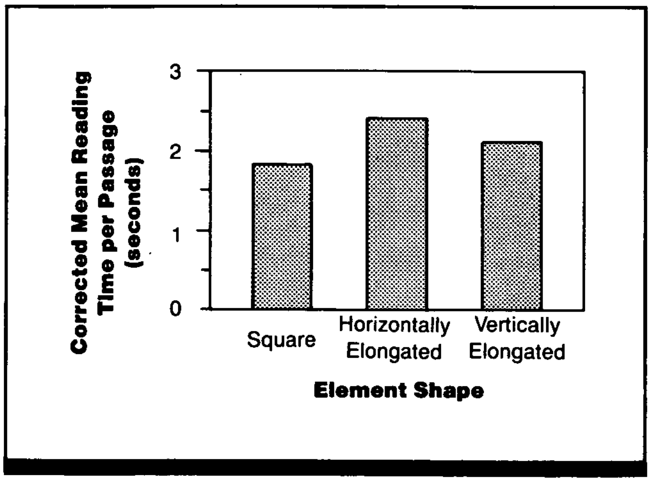

Figure 1. Effect of element shape on reading time. (Adapted from Ref. 3)

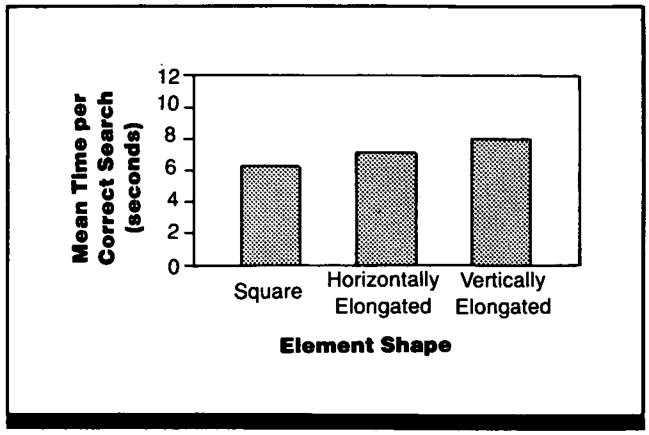

Figure 2. Effect of element shape upon random search time. (Adapted from Ref. 3)

Key Terms

Alphanumeric displays; character recognition; CRT displays; dot-matrix displays; flat panel displays; legibility; monochrome displays; reading; text displays; TV displays

General Description

The legibility of fixed element (pixel) displays is determined, in part, by the size, shape, and edge-to-edge spacing of the dots making up the characters. Display element shape is the shape of individual dots used to generate dot-matrix characters. Figures 1 and 2 show that both reading and search times on a CRT are shorter for symbols made of square elements than elements elongated horizontally or vertically.

Methods

Test Conditions

- Thirty-six alphanumeric characters, capital letters; composite of Lincoln/Mitre and two experimental fonts; characters generated using 5 x 7 dot matrices
- Element size 0.76, 1.14, and 1.52-mm; interelement spacing to edge-to-edge space/element size ratios of 0.5, 1.0, and 1.5; element shapes: square, horizontally elongated, and vertically elongated; resulting character size range from 5.3-16.7 mm in width and from 7.6-24.3 mm in height, i.e., ~16-56 min arc of visual angle in width and ~26-82 min arc in height; ambient illumination 5.4-700 lux
- Tektronix 4014-1 direct view storage tube used to display symbols; green phosphor; average display background luminance 2 cd/m^2; character luminance 17 cd/m^2; display located in light-controlled booth
- Viewing distance 1.02 m; chin rest provided; response keyboard directly in front of subject; tape recorder for oral response recording

Experimental Procedure

- Factorial design
- Independent variables: element size, interelement spacing to edge-to-edge space/element size ratio and element shape
- Dependent variables: text reading time corrected for baseline reading time, reading or target identification errors, average search time (sec) per error-free trial
- Subject's task: reading task, read one- or two-sentence passages from Tinker Speed-of-Reading Test as fast as possible, depress response key when completed, and identify inappropriate word in text; for random search task, find desired alphanumeric character from among 71 characters randomly positioned on display, depress response key, and identify character location in one of 12 display locations; for menu search task, search three columns of eight words to locate desired word, and depress response key
- 108 subjects, 61 males and 47 females

Experimental Results

- Nine random search errors and 17 menu search errors are made during 4,320 trials, i.e., errors are negligible.
- Square elements produce the shortest response times for both search and reading tasks ($p < 0.02$).
- Square elements produce the shortest response times for search and reading tasks across both levels of ambient illuminance ($p < 0.03$).

Variability

No information on variability was given.

Constraints

- Results should be applied with caution to displays other than monochrome CRTs.
- Results may be different for reading test or searching for characters presented in suboptimal environments where other displays, vibrations, or washout is present.
- Results apply only to matrix formats where the square elements' axes are parallel to the display's axes.
- Direct applications of the data presented in this entry to display systems using newer technology may be inappropriate and will require empirical validation.

Key References

1. Meister, D. (1984). *Human engineering data base for design and selection of cathode ray tube and other display systems* (NPRDC TR 84-51). San Diego, CA: Navy Personnel Research and Development Center. (DTIC No. AD A145704)

2. Semple, C. A., Jr., Heapy, R. J., Conway, E. J., Jr., & Burnette, K. T. (1971). *Analysis of human factors data for electronic flight display systems* (Tech. rep. AFFDL-TR-70-174). Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, OH. (DTIC No. AD 884770)

*3. Snyder, H. L., & Maddox, M. E. (1978, October). *Information transfer from computer-generated dot-matrix displays* (ARO 12355.7-EL). Research Triangle Park, NC: U.S. Army Research Office. (DTIC No. AD A063505)

Cross References

11.112 CRT symbol size and stroke width; effect on legibility;

11.113 CRT symbol spacing: effect on identification accuracy;

11.114 Display element size: effect on reading and search times;

11.115 Dot matrix displays: effect of inter-pixel spacing on character identification;

11.116 Dot matrix displays: effect of pixel size-spacing ratio on symbol reading time;

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification

11.208 Dot-Matrix Versus Stroke-Written Symbols: Effect on Recognition

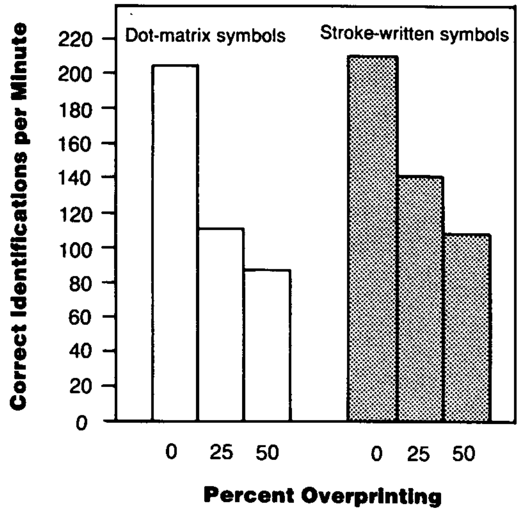

Figure 1. Correct identification per min for dot symbols and stroke symbols with 0, 25, and 50% overprinting. (From Ref. 1)

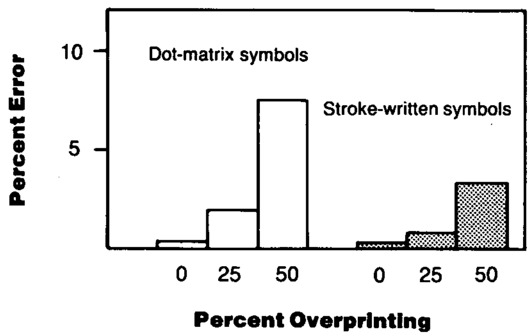

Figure 2. Percent reading errors for dot symbols and stroke symbols for 0, 25, and 50% symbol overprinting. (From Ref. 1.)

Key Terms

Alphanumeric displays; character recognition; CRT displays; display degradation; dot matrix displays; flat panel displays; symbol fonts

General Description

Two simulated CRT display character types are dot-matrix and stroke-written. Dot-matrix characters are generated by dots or points of lights arranged in a fixed matrix pattern on an electronic display. Stroke-written symbols are formed by joining different sequences of display vectors to make continuous lines. The results of legibility comparisons between the two font types indicate that they produce equal speed and about the same reading accuracy when displays are not degraded by overprinting. However, when displays are degraded by overprinting, performance is significantly better for stroke-written symbols.

Methods

Test Conditions

- 36 alphanumeric characters presented with a rear projection slide projector onto a Luxchrome screen with light transmission of 50%; symbol height of 12-18 TV lines
- Three display fonts: one 7 x 11 dot matrix and two stroke-written; stroke symbols were recreations of Hughes 407L and Burroughs BUIC alphanumerics; symbols graphically drawn according to rules for each character generation scheme
- Subject seated at comfortable viewing distance from display; symbol height: 22 min arc of visual angle at subject's eye; headrest used to control viewing distance
- Symbol stroke luminance 51.4-68.6 cd/m^2; symbol-to-background luminance contrast 10:1
- Room illumination with overhead fluorescent lights: 107-161 lux
- Each stimulus slide contained 12 characters in two rows and six columns
- Characters degraded by overprinting method where one symbol is vertically superimposed over a second symbol with 0, 25, or 50% overlap

Experimental Procedure

- Mixed within- and between-groups design
- Independent variables: display font, degree of overprinting
- Dependent variables: number of reading errors, number of correct symbol identifications per min
- Observer's task: identify characters presented on screen and read responses aloud
- 12 observers

Experimental Results

- No performance differences are found between the two stroke fonts. Thus, data for both fonts are combined (Figs. 1, 2).
- There are no performance differences between the dot-matrix and stroke-written fonts when displays are not degraded by overprinting.
- Rate of correct symbol recognition is significantly higher for stroke-generated symbols only under the 25% overprinting condition.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

• When symbols are overprinted, significantly ($p < 0.05$) more errors of identification are made for dot-matrix symbols than for stroke-written symbols, under both overprinting conditions.

Variability

No information on variability was given.

Constraints

• Results are limited to fonts highly similar in form and size to the ones tested.
• Results might not be consistent under different types of image degradation or for reading blocks of text instead of single characters.
• Displays used were monochrome. Color display applications will require empirical validation.

Key References

*1. Shurtleff, D. A. (1980). *How to make displays legible*. La Mirada, CA: Human Interface Design.

2. Van Cott, H.I., & Kinkade, R.G. (Eds.). (1972). *Human engineering guide to equipment design*. Washington, DC: U.S. Government Printing Office.

Cross References

11.112 CRT symbol size and stroke width: effect on legibility;

11.113 CRT symbol spacing: effect on identification accuracy;

11.114 Display element size: effect on reading and search times;

11.116 Dot matrix displays: effect of pixel size-spacing ratio on symbol reading time;

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification;

11.207 Display element shape: effect on reading and search times

11.209 Alphanumeric Font and Display Legibility

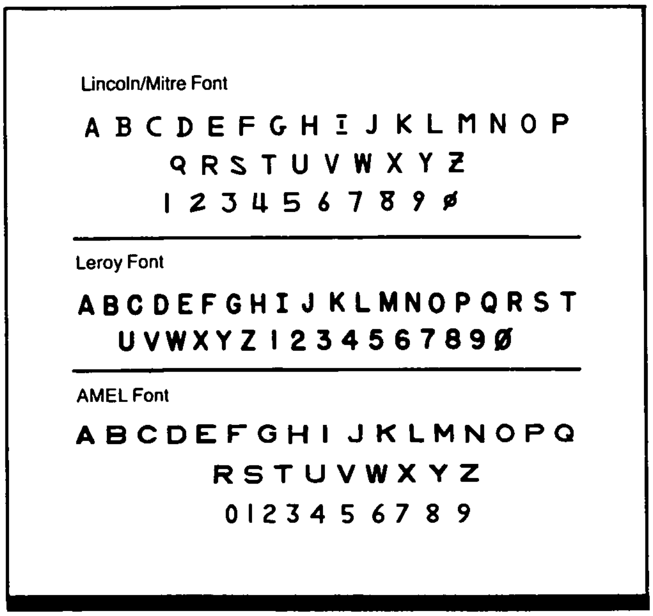

Figure 1. Examples of alphanumeric fonts suitable for electronically generated display applications.

Key Terms

Alphanumeric coding; AMEL font; character recognition; CRT displays; fonts; Hazeltine font; information display; legibility; Leroy font; Lincoln-Mitre font

General Description

The font of an alphanumeric character set refers to the shape or geometry of the characters. Several fonts have been developed to improve reading speed and accuracy and to reduce confusion among similar-appearing characters (e.g., 2 and Z). Highly legible fonts are characterized by acceptable height-to-width ratios and strokewidths, a basically vertical orientation, and the lack of extraneous detail, such as serifs (Ref. 1). Research to date has focused on improving identification accuracy and speed for particular character set configurations or comparing relative legibilities of different character sets (Refs. 2, 3). Research results indicate that the following fonts appear to be satisfactory for electronically generated display application: Leroy, Lincoln/Mitre, AMEL, and Hazeltine (Ref. 1). Also, there is no experimental evidence to indicate that the use of a unique font for TV displays will reduce resolution requirements (Ref. 3).

Applications

The selection of alphanumeric fonts for information presentation on electronically generated displays.

Constraints

- The legibility of an alphanumeric character set on an electronically generated display assumes that at least minimum values are met for other important factors, including vertical and horizontal resolution, direction of scan, contrast direction, symbol-to-background luminance contrast, symbol spacing, symbol size, and stroke width.
- The fonts recommended here may be only generally applicable to matrix-generated displays. Other important design parameters for dot-matrix displays include number of dots in the matrix, dot element shape, and dot separation.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Meister, D. (1984, July). *Human engineering data base for design and selection of cathode ray tube and other displays* (NPRDC-TR 84-51). San Diego, CA: Naval Personnel Research and Development Center. (DTIC No. ADA145704)

*2. Semple, C. A., Heapy, R. J., Conway, E. J., & Burnette, K. T. (1971, January). *Analysis of human factors data for electronic flight display systems* (AFFDL-TR-70-174). Dayton, OH: Wright-Patterson Air Force Base. (DTIC No. AD884770)

*3. Shurtleff, C. A. (1980). *How to make displays legible*. La Mirada, CA: Human Interface Design.

Cross References

10.413 Display legibility during vibration: effect of character subtense;

10.414 Display legibility during vibration: effect of character spacing;

10.415 Display legibility during vibration: effect of character font during whole-body vibration;

11.108 Television display resolution: effect on time and accuracy for symbol identification;

11.111 CRT symbol size and resolution: effect on legibility;

11.112 CRT symbol size and stroke width: effect on legibility;

11.113 CRT symbol spacing: effect on identification accuracy;

11.114 Display element size: effect on reading and search times;

11.115 Dot matrix displays: effect on inter-pixel spacing on character identification;

11.116 Dot matrix displays: effect of pixel size-spacing ratio on symbol reading time;

11.117 Dot-matrix displays: effect of matrix size on speed and accuracy of symbol identification;

11.207 Display element shape: effect on reading and search times

11.210 Time and Accuracy in Reading Linear Scales

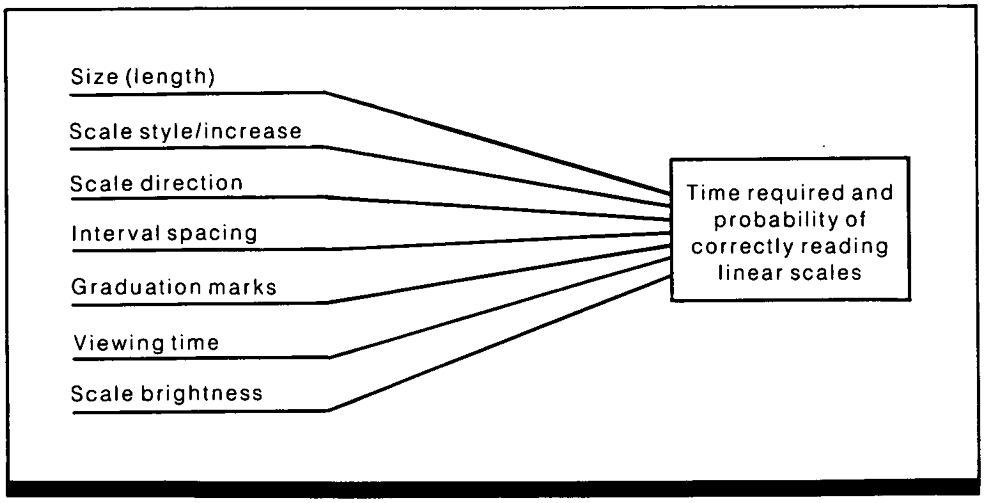

Figure 1. Characteristics affecting the time and accuracy of reading linear scales.

Key Terms

Error probability; human performance reliability; information portrayal; linear scales; response time

General Description

Response time and the probability of correctly reading linear scales (based on 10,000 reading opportunities) (Ref. 1) vary with the characteristics shown in the figure and the table. To use available data, the equipment or system whose performance is to be predicted or evaluated is analyzed to determine which controls and displays are used and which equipment characteristics are relevant. If linear scales are involved, probability and time information are extracted from the table. To determine the time required to read the linear scale, the time for each scale characteristic found in the actual equipment is extracted from the table and added to the base time. To determine the probability of correctly reading the scale, probabilities for each relevant scale characteristic are extracted from the table and multiplied serially.

Applications

The data shown in the table can be used to perform reliability analyses, make human error predictions, and select linear scale components.

Constraints

Serial multiplication of individual characteristics probably underestimates the probability of correctly reading the scales.

Key References

1. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* [AIR-C43-1/62-RP(1)]. Pittsburgh, PA: American Institute for Research. (DTIC No. AD607161)

Cross References

7.102 Human reliability analysis;
7.103 Technique for human error rate prediction (THERP);
7.108 Probability of correctly reading meters;
11.211 Scale divisions: reading to the nearest scale mark;
11.212 Scale divisions: straight scale interpolation;
11.214 Time and accuracy in reading circular scales

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Time required and probability of correctly reading linear scales.

Base Time—1.00 min

Time Added	Human Reliability	Linear Scales
		1. Size (length)
1.05	0.9997	a. 3 in.
0	0.9998	b. 6 in.
0.15	0.9996	c. 9 in.
		2. Scale style
		a. Quantitative reading to determine a specific value
0.90	0.9979	(1) Moving pointer
0.90	0.9970	(2) Moving scale
		b. Qualitative reading or checking to determine whether indication is within a certain range.
0.30	0.9969	(1) Moving scale
0.15	0.9976	(2) Moving pointer
0	0.9999	(3) Color coded
		3. Scale direction
0	0.9998	a. Horizontal
0.40	0.9995	b. Vertical
		4. Distance between scale marks
1.50	0.9975	a. 1/10 in. or less
0.75	0.9992	b. 1/10-1/4 in.
0	0.9982	c. 1/4 in. or more
		5. Number of graduation marks per unit of required resolution
		(1. Define required resolution, e.g., must read to 5 deg
		2. Determine number of graduation marks used for each five degrees represented on the scale)
0	0.9998	a. Every one or two units
1.13	0.9990	b. Every 5th unit
1.88	0.9985	c. Every 10th unit or log scales
		6. Number of units represented
0	0.9998	a. 50-100
0.55	0.9988	b. 200
1.45	0.9968	c. 400
		7. Scale increase
0	0.9998	a. Left to right (or bottom to top)
0.55	0.9992	b. Right to left (top to bottom)
		8. Proportion of graduation marks numbered
0	0.9999	a. 1:1 or 1:2
0.45	0.9995	b. 1:5
1.60	0.9985	c. 1:10
		9. Exposure (viewing) time
0.24	0.9952	a. 0.12 sec
0.03	0.9983	b. 0.30-0.36 sec
0.02	0.9996	c. 1.00 sec
0	0.9999	d. Indefinite
		10. Scale brightness
2.45	0.9975	a. Imperceptible from normal viewing position
1.20	0.9962	b. Minimally perceptible from normal position
0	09999	c. Easily perceptible from normal position

11.211 Scale Divisions: Reading to the Nearest Scale Mark

Table 1. Time and error scores for four conditions of quantitative dial scale reading. (From Ref. 1)

	Scale Graduation and Reading Conditions							
	5/5		1/5		1/1		5/1	
	Time*	Error**	Time	Error	Time	Error	Time	Error
Open-Window Display	1.02	.85	1.03	0.85	1.21	0.00	1.22	12.10
Round Dial Display	1.13	2.50	1.16	2.90	1.47	2.50	1.39	9.15
Vertical Linear Scale Display	1.18	3.35	1.18	0.40	1.49	3.35	1.43	13.75

*Display reading time

**Percent of display readings in error

Key: 5/ scale graduated by fives; 1/ scale graduated by ones; /5 scale read to nearest five; /1 scale read to nearest one

Key Terms

Circular scales; dial reading; dials; graduation marks; information portrayal; reading error; scale divisions; straight scales

General Description

Some methods of dividing numbered scale intervals cause slower reading and more errors than others do. An experiment was conducted to test the effects of scale divisions on reading accuracy and speed. Major scale graduations were marked and numbered at increments of 10 units, from 0-100. Midpoint scale marks always occurred at increments of 5 units. On some scales, single units also were marked. Units of 5 and 1 were not numbered. Scales marked with 20 graduations are read more accurately than scales marked with 100 graduations. The highest accuracy scores are obtained when the scales are graduated by ones and read to the nearest five units. The lowest accuracy scores are obtained in the condition where scales are graduated by fives and read to the nearest single unit. Response times (reading speeds) are not significantly different in each of the four conditions of scale graduation.

Methods

Test Conditions

- Three scales used: circular, vertical, and open window; scale graduation: 20 or 100 divisions; scales presented as pictures by tachistoscope with a sliding mirror attachment
- Luminance was 1030 cd/m^2; exposure fields of 53 x 53 cm
- Viewing distance 71 cm
- Viewing or exposure time varied from 120-1080 msec for controlled viewing; in one condition, observer controlled viewing time
- Observers randomly assigned to conditions; conditions counterbalanced

Experimental Procedure

- Within-subjects factorial design
- Independent variables: scale shape, scale graduation, scale reading, viewing time
- Dependent variables: scale reading accuracy, response time
- Observer's task: read a dial (to nearest 5 or 1 units) and vocalize a response
- 12 observers

Experimental Results

- Dial reading is more accurate with 20-division scales than with 100-division scales.
- When subjects are allowed as much time as they want to read scales, there are no differences in accuracy between the vertical, circular, and open window scales.
- Subjects are more accurate in reading scales marked by ones and read in units of five rather than reading scales marked by fives and read by ones. Thus, it appears that with a more difficult reading task, interpretation errors increase.
- Response time increases with shortened exposure time and with increases in scale reading complexity.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Results reported in Ref. 2 support the conclusion that scales using more divisions are more difficult to read. For example, subjects make more errors when they read dials with 600 divisions and fewer errors with a 50-division scale.

Constraints

- Different results may be found when reading actual dials; this experiment only used photographs of dials.
- Results may not be directly applicable to electronically generated scales.
- Results might also be different for older observers, since visual acuity typically decreases with age, especially at low light levels.
- The results are limited to the scale values used.
- Different illumination or other environmental conditions might affect the reading of scales.

Key References

*1. Elkin, E. H. (1959). *Effects of scale shape, exposure time, and display-response complexity on scale reading efficiency* (WADC-TR-58-472). Wright-Patterson AFB, OH: Wright Air Development Center. (DTIC No. AD208381)

2. Kappauf, W. E., & Smith, W. M. (1948, July). *Design of instrument dials for maximum legibility: II. A preliminary experiment on dial size and graduation* (MCREXD-694-1-N). Wright-Patterson AFB, OH: Air Material Command. (DTIC No. ADF630361)

3. Kappauf, W. E., & Smith, W. M. (1950, July). *Design of instrument dials for maximum legibility: IV. Dial graduation, scale range and dial size as factors affecting the speed and accuracy of scale reading* (Tech. Rep. 914). Wright-Patterson AFB, OH: Air Material Command. (DTIC No. ADF630293)

4. Semple, C. A. Jr., Heapy, R. J., Conway, E. J. Jr., & Burnette, K. T. (1971). *Analysis of human factors data for electronic flight displays* (AFFDL-TR-70-174). Wright-Patterson AFB, OH: Air Force Flight Dynamics Laboratory. (DTIC No. AD884770)

5. Vernon, M. D. (1946, July). *Scale and dial reading* (APU.49). Cambridge, U. K.: Flying Personnel Research Committee, Medical Research Council Unit of Applied Psychology, Psychological Laboratory. (DTIC No. AD084856)

Cross References

7.108 Probability of correctly reading meters;

11.210 Time and accuracy in reading linear scales;

11.212 Scale divisions: straight scale interpolation;

11.214 Time and accuracy in reading circular scales;

11.215 Scale divisions: reading circular dials;

11.216 Time and accuracy in reading semi-circular scales

11.212 Scale Divisions: Straight Scale Interpolation

Key Terms

Dial reading; graduation marks; horizontal scales; information portrayal; reading error; scale divisions; scale interpolation; scales; vertical scales

General Description

Lowest error rates and shortest response times for reading simulated straight scales are found when there is an internal length of 4.8 cm between major graduations. As the scale size increases or decreases from 4.8 cm, reading speed and accuracy both decrease. A scale with nine or four graduation marks produces fewest identification errors. Horizontal scales are read more quickly than vertical scales, although reading accuracy is similar for the two scales. Reading scales at 10 or 100 times the marked scale value does not significantly affect reading speed or accuracy.

Methods

Test Conditions

- Transparent slides of drawn instrument scales back-projected to yield 22-x 3-cm images; scale values ranging from 11-99; black scale marks and numerals on white backgrounds
- Internal length (distance between numbered units on the scale) ranged from 0.6 -6 cm (¼ to 2⅜ in.); 0, 3, 4, or 9 graduation marks between each unit on horizontal and vertical scales
- Viewing distance 71 cm
- Light-proof room; black environmental background; no dark adaptation period provided; illumination level not reported, but sufficient for experimenter to make written records of subject's responses.
- Three power-of-10 reading conditions: scale number x 10, x 100, or x 1000
- Observers viewed all combinations of interval lengths and orientations, but only one graduation mark and a power-of-10 reading condition; 150 readings per subject; presentation orders randomized

Experimental Procedure

- Mixed design
- Independent variables: interval length; scale orientation; number of graduation marks per major graduation; power-of-10 reading condition.
- Dependent variables: absolute error in reading displayed values, response time
- Observer's task: after displayed valued identified, press a hand-held button to stop response time clock and read scale value aloud
- 150 observers, Air Force officers with 20/20 vision (corrected or uncorrected)

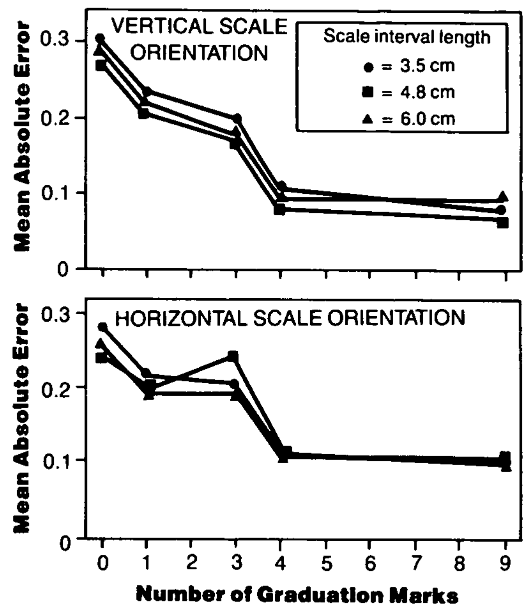

Figure 1. Mean absolute error as a function of scale interval length and number of graduation marks per interval for horizontal and vertical scales. (From Ref. 4)

Experimental Results

- A 4.8-cm interval length produces the fewest reading errors.
- A 6-cm interval length produces a deterioration of reading speed, and a 3.5-cm interval length produces more errors.
- Nine graduation marks yield the smallest average reading error; fewer than four graduation marks produces substantially higher reading errors and longer reading times.
- Horizontal scales are read somewhat more quickly than vertical scales, but reading errors are similar on both types of scale.
- The power-of-10 reading format has no significant effect.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The results are consistent with finding (Ref. 2) that an optimal interval length for reading scales is 3.8 cm. Churchill used an interpolation task, which might be the reason for this 1-cm discrepancy.

Constraints

- The values obtained may be valid only for stationary scales.
- Different results may occur under non-uniform or lower illumination.
- These values may be different when distracting stimuli, such as other displays, are present.
- It is possible that different results would be obtained with different colored scales.
- Shorter viewing times might yield different results.
- Results may not be directly applicable to electronically generated displays.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Carr, W. J., & Garner, W. R. (1952). The maximum precision of reading fine scales. *Journal of Psychology, 34*, 85-94.

2. Churchill, A. V. (1959). Optimal interval length for visual interpolation: The effect of viewing distance. *Journal of Applied Psychology, 43*, 125-128.

3. Churchill, A. V. (1956). The effect of scale interval and pointer clearance on speed and accuracy of interpolation. *Journal of Applied Psychology, 40*, 358-361.

*4. Kelso, B. J. (1965). Legibility study of selected scale characteristics for moving-tape instruments. *Human Factors, 7*, 545-554.

Cross References

7.108 Probability of correctly reading meters;

11.210 Time and accuracy in reading linear scales;

11.211 Scale divisions: reading to the nearest scale mark;

11.215 Scale divisions: reading circular dials

Table 1. Mean response time as a function of scale reading conditions. (From Ref. 4)

		Graduation Marks					
Scale Interval Length (cm)	Orientation	0	1	3	4	9	Overall
3.5	V	5.54	3.76	4.11	4.47	3.69	4.31
	H	5.59	3.59	4.00	4.76	3.54	4.30
4.8	V	5.75	3.65	4.02	4.64	3.59	4.33
	H	5.40	3.68	3.97	4.56	3.41	4.20
6.0	V	6.06	3.79	4.27	4.81	3.58	4.50
	H	5.78	3.64	4.04	4.54	3.35	4.27

11.213 Dial Reading Errors for Various Scale Intervals

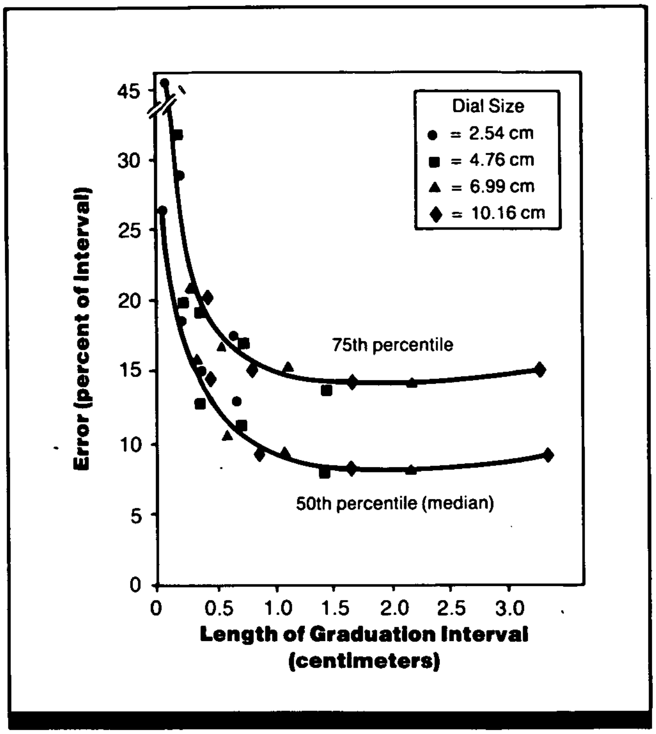

Figure 1. Errors in dial reading (interpolation) with error expressed as a percentage of the graduation interval. Data are for the four dial sizes shown in the legend. (From Ref. 2)

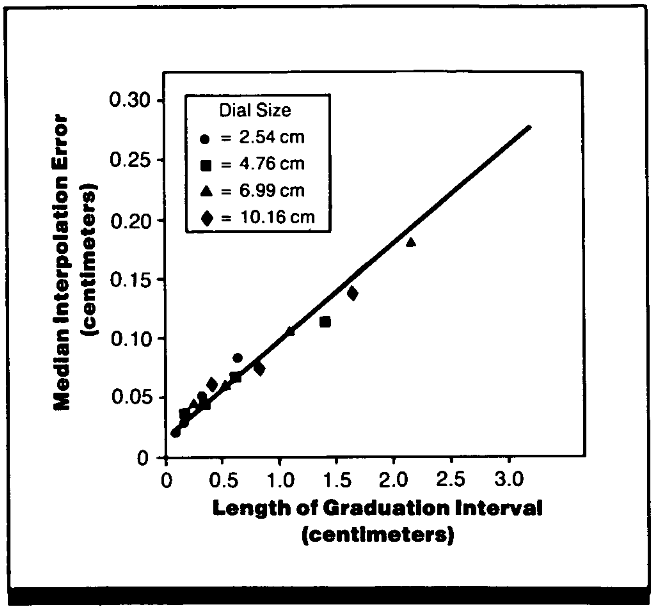

Figure 2. Error data for Fig. 1 replotted as absolute values. (From Ref. 2)

Key Terms

Dial reading; dial size

General Description

A number of studies have considered the design of dials, as it affects accuracy in reading dial scales. In particular, the general size of dials and the size of dial scale intervals have been examined. The results discussed in this entry are for normal conditions of viewing; other factors might affect the design outcome under unusual conditions.

When conditions permit prolonged or leisurely checking, accuracy of reading increases as dial size increases. On the other hand, an intermediate-sized dial will be optimal under quick check conditions; scales should be large enough to be accurately gauged, but the location of the pointer in space should not be highly uncertain. One study (Ref. 1) found optimal dial size under normal conditions to be ~4.45 cm (1.75 in.)

Figure 1 presents data from an experiment that examined relative error in interpolation and provides information about optimal scale interval when error is expressed as a percentage of graduation interval size. As the figure shows, error decreases as a proportion of scale graduation as graduation size increases to ~1.28 cm (0.5 in.). Graduation size >1.28 cm has little effect.

The data from Fig. 1 are replotted in Fig. 2 to express error in absolute terms. For all dial sizes, error decreases as scale intervals are made finer (Ref. 2). Reference 3 obtained roughly similar results, but found increased errors at very small graduations: thus the optimal graduation is 1.28 cm, subtending 6 min of visual angle (Refs. 1, 3).

Constraints

- Specific optimal values in any situation may be affected by factors such as pointer design, lighting, length, and thickness of scale marks.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Fitts, P. M. (1966). Engineering psychology and equipment design. In S. S. Stevens (Ed.), *Handbook of experimental psychology* (pp. 1287-1340). New York: Wiley.

*2. Grether, W. F., & Williams, A. C., Jr. (1947). Speed and accuracy of dial reading as a function of dial diameter and angular spacing of scale divisions. In P. M. Fitts (Ed.), *Psychological research on equipment design* (pp. 101-109). Washington, DC: U.S. Government Printing Office.

3. Kauppof, W. E., & Smith, W. M. (1948). *Design of instrument dials for maximum legibility: II. A preliminary experiment on dial size and gradation* (MCREXD-694-1N). Washington, DC: USAF Air Material Command Memorandum (DTIC No. ADF630361)

Cross References

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

11.211 Scale divisions: reading to the nearest scale mark;

11.212 Scale divisions: straight scale interpolation

11.214 Time and Accuracy in Reading Circular Scales

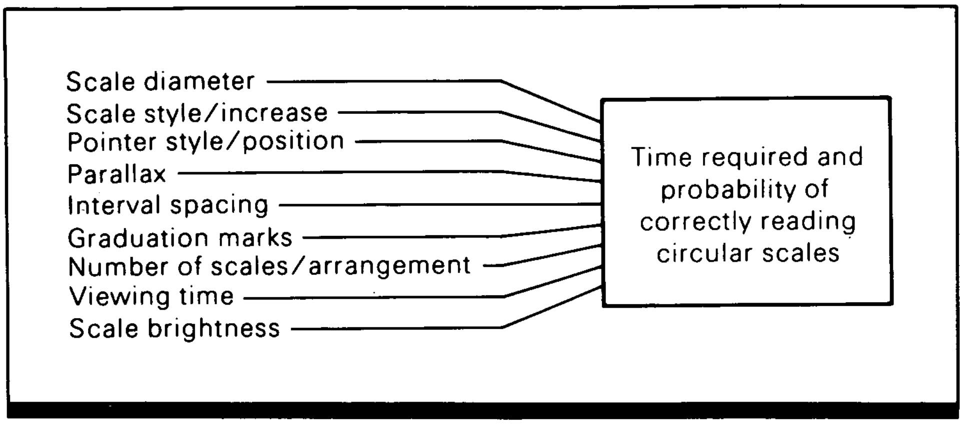

Figure 1. Characteristics affecting the time and accuracy of reading circular scales.

Key Terms

Circular scales; error probability; human performance reliability; information portrayal; response time

General Description

Data describing the time taken and accuracy of reading circular scales are available through a data bank called the Data Store (Ref. 1). The Data Store is organized around common controls and displays (e.g., knobs and meters). It contains performance data taken from 164 psychological studies (out of over 2000 examined), describing the errors and times involved in operating controls and displays with varying characteristics. Figure 1 indicates the characteristics affecting performance with circular scales. The Data Store indicates the probability of successfully operating these instruments as a function of their characteristics and the minimum time needed to operate them.

To use the Data Store, the equipment or system whose performance is to be predicted or evaluated must be analyzed to determine which controls and displays are used and which component characteristics are relevant. Probability and time information for these components and characteristics are then extracted from the Data Store. Probabilities are based on the equation: 1.0 (completely accurate performance) minus error frequency n per 10,000 opportunities to use the control or display: $p = 1 - (n/10{,}000)$. Individual tables are available for common controls and displays.

The human reliability of any control/display component is a function of individual characteristics that describe that component. The human reliability of any task is a function of the human reliabilities for individual controls and displays used in that task. Human reliability of any operation consisting of n tasks is therefore a function of individual human reliabilities for the tasks comprising that operation. A measure of equipment operability for any component, task, or operation is developed by extracting probabilities from the table and multiplying them serially for the individual component characteristics, components, and tasks. To determine the time required to read the scale, the time for each scale characteristic is extracted from the table and added to the base time.

Applications

The table describes the probability of correctly reading circular scales, together with estimates of the time needed to read them correctly. These data can be used in performing human reliability analyses, making human error rate predictions, and selecting scale components.

Constraints

- Serial multiplication of individual parameters probability underestimates actual probability of correctly reading scales.

Key References

1. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* [AIR-C43-1/62-RP(1)]. Pittsburgh, PA: American Institute for Research. (DTIC No. AD607161)

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.108 Probability of correctly reading meters;

11.210 Time and accuracy in reading linear scales;

11.215 Scale divisions: reading circular dials;

11.216 Time and accuracy in reading semicircular scales

Table 1. Time required and probability of correctly reading circular scales.

Base Time—0.50 min

Time Added	Human Reliability	Circular Scales
		1. Scale diameter
1.03	0.9996	a. 1 in.
0	0.9997	b. 1.6-1.75 in.
0.03	0.9993	c. 2.75 in.
		2. Scale style
		a. Quantitative reading to determine a specific value
1.50	0.9966	(1) Moving pointer
1.50	0.9967	(2) Moving scale
		b. Qualitative reading and checking to determine whether indication is within a certain range
0.25	0.9965	(1) Moving scale
0.25	0.9975	(2) Moving pointer
0	0.9999	(3) Color coded
		3. Pointer style
0	0.9990	a. Conventional, horizontal bar, 0 at base
1.40	0.9987	b. Triangle or vertical bar at base (Pointer base—short end of pointer)
3.50	0.9900	4. Parallax factor
		5. Distance between scale marks
2.70	0.9975	a. Less than 1/20 inch
1.10	0.9986	b. More than 1/20-1/4 inch
0	0.9996	c. More than 1/4-2 inch
		6. Number of graduation marks per unit of required resolution (1. Define required resolution, e.g., must read to 5 deg 2. Determine number of graduation marks used for each five degrees represented on the scale)
0	0.9996	a. Every one or two units
2.56	0.9985	b. Every 5th unit
2.78	0.9975	c. Every 10th unit or log scales
		7. Proportion of graduation marks numbered
0	0.9999	a. 1:1
0.50	0.9991	b. 1:5
2.00	0.9980	c. 1:10
		8. Number of units represented
0	0.9996	a. 50-100
0.50	0.9984	b. 200
1.50	0.9962	c. 400
2.50	0.9952	d. 600
		9. Scale brightness
2.50	0.9965	a. Imperceptible from normal viewing position
1.75	0.9955	b. Minimally perceptible from normal position
0	0.9995	c. Easily perceptible from normal position
		10. Alignment position of pointer (Position assumed by pointer when condition is neutral or normal)
		a. All dials uniform (identical markings)
0.75	0.9985	(1) 3 o'clock
0.35	0.9992	(2) 6 or 12 o'clock
0	0.9994	(3) 9 o'clock
		b. Mixed dials (dissimilar markings)
0.43	0.9990	(1) 3 o'clock
0.35	0.9985	(2) 9 or 12 o'clock
		11. Number of scales and arrangement
0	0.9999	a. 1 or 2 x 1
1.10	0.9997	b. 2 x 2, 2 x 4, 4 x 4
3.85	0.9990	c. 4 x 10, 6 x 4
5.10	0.9975	d. 8 x 4, 9 x 5
		12. Scale increase
0.55	0.9996	a. Right to left
0	0.9999	b. Left to right
		13. Exposure (viewing) time
0	0.9997	a. Indefinite
0.20	0.9996	b. 0.08-0.15 sec
0.06	0.9966	c. 0.30-0.70 sec
0.04	0.9977	d. 1.0-1.40 sec

11.215 Scale Divisions: Reading Circular Dials

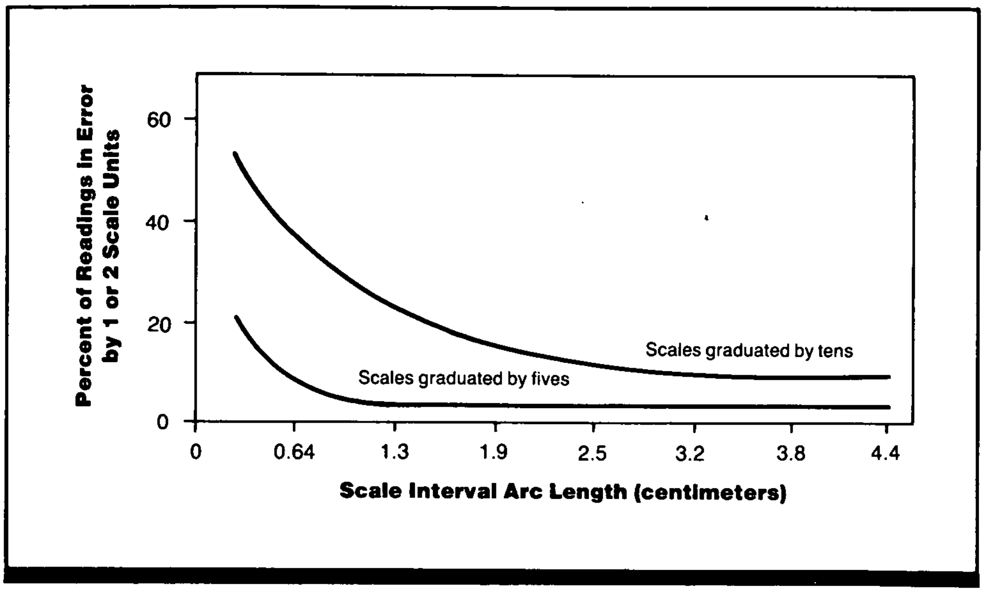

Figure 1. Probability of minor dial scale reading errors (1 or 2 units) as a function of scale interval length. (Data from Ref. 3)

Key Terms

Circular scales; dial reading; graduation marks; information portrayal; numerical scales; reading error; scale divisions

General Description

When reading 7.1-cm and 3.6-cm diameter dials, a larger scale interval, in terms of min arc of visual angle, results in fewer reading interpolation errors. Scales with fewer minor graduation marks (e.g., five) are interpolated with fewer errors than scales with more (e.g., 10) minor graduation marks. Thus, within the ranges tested, as the scale interval is expanded and fewer minor graduation marks are used, reading accuracy improves.

Methods

Test Conditions

- Numeric 360-deg dials were presented as high-contrast photographic prints, white dial markings on black background; dial diameters: 7.1 and 3.6 cm; dial marking luminance: 10 cd/m^2; scale interval values: 50, 100, 200, 400, or 600; dial graduation schemes: 1, 2, 5, and 10 units
- 12 dials presented/trial; observer sat in light controlled booth; chin in a chin-rest 71 cm from dials
- 50-60 observations per observer per dial
- Observers viewed dials under all conditions of independent variables; observers randomly assigned to conditions; conditions counterbalanced

Experimental Procedure

- Within-subjects design
- Independent variables: size of dial; graduation type; scale interval values
- Dependent variables: dial reading accuracy, response time
- Observer's task: read numerical values of the stimuli dials to nearest whole unit
- 20 observers with at least 20/20 vision

Experimental Results

- Scales graduated in units of ten yield a higher percentage of reading errors than scales graduated in units of 5, 2, or 1.
- Larger intervals between scale graduations produce fewer reading errors than shorter intervals.
- There is no interaction between the graduation scheme and the scale interval. Thus, the effect of larger scale intervals producing fewer reading errors is consistent over all graduation conditions.
- Larger diameter dials are read somewhat less accurately, even when distances between scale graduations are the same for both dial sizes. This is attributed to greater scale graduation mark and pointer thicknesses in the larger dials.
- The larger dials are read slightly but significantly faster.
- Reading time decreases substantially and significantly as distance between scale graduations increases.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The results are in agreement with other studies (Refs. 1, 4) which also show that accuracy of interpolation between scale marks increases, within the ranges studied. Also, reading accuracy is essentially independent of display size and arrangement of scale marks.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Different results may be found when reading actual dials, as this experiment used only dial photographs.
- Results might be different for older subjects, since acuity decreases with age, especially at low light levels.
- Results are limited to the scale shape and values investigated.
- Differences in illumination or other environmental conditions might yield different results.

Key References

1. Grether, W. F., & Williams, A. C. (1949). Psychological factors in instrument reading: II. The accuracy of pointer position interpolation as a function of the distance between scale marks and illumination. *Journal of Applied Psychology, 33*, 594-604.

2. Kappauf, W. E., & Smith, W. M. (1948, July). *Design of instrument dials for maximum legibility: II. A preliminary experiment on dial size and graduation* (MCREXD-694-1-N). Wright-Patterson AFB, OH: Air Material Command. (DTIC No. ADF630361)

*3. Kappauf, W. E., & Smith, W. M. (1950, July). *Design of instrument dials for maximum legibility: IV. Dial graduation, scale range and dial size as factors affecting speed and accuracy of scale reading* (AF-TR-5914-PT-4). Wright-Patterson AFB, OH: Air Material Command. (DTIC No. ADF630293)

4. Leyzorek, M. (1949). Accuracy of visual interpolation between circular scale markers as a function of the separation between markers. *Journal of Experimental Psychology, 39*, 270-279.

Cross References

7.108 Probability of correctly reading meters;

11.211 Scale divisions: reading to the nearest scale mark;

11.212 Scale divisions: straight scale interpolation;

11.214 Time and accuracy in reading circular scales;

11.216 Time and accuracy in reading semi-circular scales

11.216 Time and Accuracy in Reading Semi-Circular Scales

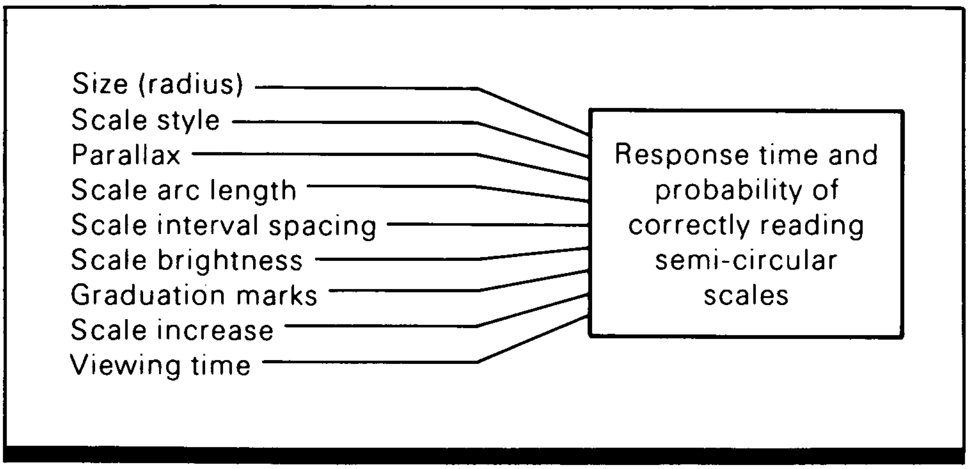

Figure 1. Characteristics affecting time and accuracy in reading semi-circular scales.

Key Terms

Error prediction; error probability; human performance reliability; information portrayal; response time; semi-circular scales

General Description

Response time and the probability of correctly reading semi-circular scales (based on an error frequency per 10,000 observations, subtracted from errorless performance, 1.0) vary with the characteristics shown in the figure and the table. To develop a human reliability measure of performance, the equipment/system must be analyzed to determine which characteristics in the figure are relevant. Then probability values for all relevant scale characteristics are extracted from the table and multiplied serially. Response times for each relevant characteristic are extracted from the table and added to the base time value.

Applications

The data shown in the table can be used to perform human reliability analyses, make human error rate predictions, and select semi-circular scale components.

Constraints

- Serial multiplication of individual parameters probably underestimates actual probability of correctly reading the scales.

Key References

1. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* [AIR-C-43-1/62-RP(1)]. Pittsburgh, PA: American Institute for Research. (DTIC No. AD607161)

Cross References

7.102 Human reliability analysis;

7.103 Techniques for human error rate prediction (THERP);

7.108 Probability of correctly reading meters;

11.211 Scale divisions: reading to the nearest scale mark;

11.214 Time and accuracy in reading circular scales;

11.215 Scale divisions: reading circular dials

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Response time and probability of correctly reading semi-circular scales.

Base Time—0.50 min

Time Added	Human Reliability	Semi-Circular Scale (Includes open-window scales)
		1. Size (radius)
1.15	0.9996	a. ½-¾ in.
.05	0.9997	b. ¾-1 in.
0	0.9993	c. 1-2 in.
		2. Scale style
		a. Quantitative information to determine a specific value
1.10	0.9980	(1) Moving pointer
1.10	0.9981	(2) Moving scale
		b. Qualitative information and checking to determine whether indication is within a certain range.
0.10	0.9982	(1) Moving pointer
0.10	0.9975	(2) Moving scale
0	0.9999	(3) With color or zone code
3.50	0.9900	3. Parallax
		4. Scale arc length (number of degrees included by scope face)
0.13	0.9937	a. 25 deg
0	0.9950	b. 50-100 deg
0.01	0.9964	c. 200 deg
		5. Scale interval spacing (Distance between graduation marks)
1.00	0.9965	a. <1/20 in.
0.10	0.9933	b. 1/20-<1/10 in.
0	0.9955	c. 1/10-<1/2 in.
0	0.9969	d. 1/2-<1 in.
0.16	0.9962	e. 1-<2 in.
		6. Scale brightness
2.49	0.9971	a. Imperceptible from normal viewing position
0.35	0.9960	b. Minimally perceptible from normal position
0	0.9998	c. Easily perceptible from normal position
		7. Number of graduation marks per unit of required resolution
		(1. Define required resolution, e.g., must read to 5 deg
		2. Determine number of graduation marks used for each five degrees represented on the scale)
0	0.9996	a. Every 1 or 2 units
1.45	0.9992	b. Every 5th unit
1.75	0.9985	c. Every 10th unit
		8. Proportion of graduation marks numbered
0	0.9999	a. 1:1 or 1:2
0.80	0.9995	b. 1:5
1.50	0.9985	c. 1:10
		9. Scale increase
0	0.9999	a. Left to right
0.55	0.9996	b. Right to left
		10. Exposure (viewing) time
0.20	0.9956	a. 0.075-0.15 sec
0.06	0.9966	b. 0.30-0.70 sec
0.04	0.9977	c. 1.0-1.4 sec
0	0.9997	d. Indefinite

11.217 Time and Accuracy in Reading Counters

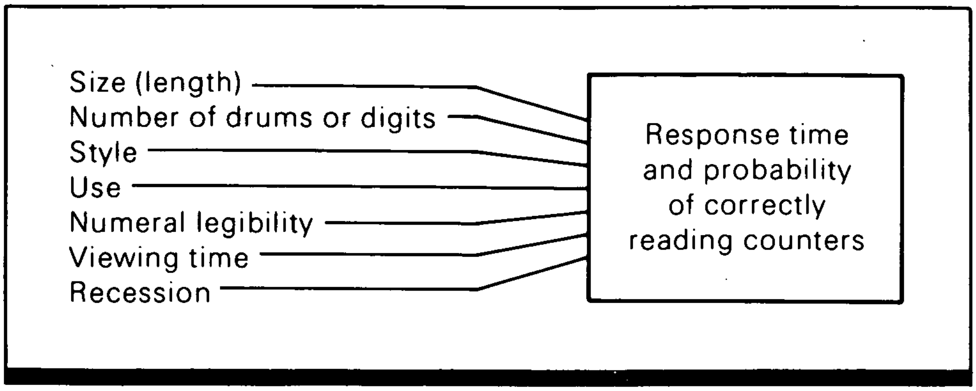

Figure 1. Characteristics affecting time and accuracy in reading counters.

Key Terms

Counters; error prediction; human performance reliability; response time

General Description

Response time and probability of correctly reading counters (based on error frequency per 10,000 observations subtracted from errorless performance, 1.0) vary with the characteristics shown in the figure and table. To develop a human reliability measure of performance, the equipment/system must be analyzed to determine which characteristics in the figure are relevant. The probability values for all relevant counter characteristics are extracted from the table and multiplied serially. Response times for each relevant characteristic are extracted from the table and added to the base time value.

Applications

The data presented in the table can be used to perform human reliability analyses and make human error rate predictions.

Constraints

- Serial multiplication of individual parameters probably underestimates actual probability of correctly reading the counters.

Key References

1. Munger, S. J., Smith, R. W., & Payne, D. (1962, January). *An index of electronic equipment operability: Data Store* [AIR-C43-1/62-RP(1)]. Pittsburgh, PA: American Institute for Research. (DTIC No. AD607161)

Cross References

7.102 Human reliability analysis;

7.103 Technique for human error rate prediction (THERP);

7.104 Human performance data and sources;

11.214 Time and accuracy in reading circular scales

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Response time and probability of correctly reading counters.

Base Time—0.50 min

Time Added	Human Reliability	Counters
		1. Size (length in inches)
0.75	0.9990	a. 1
0	0.9998	b. 1-2
0.10	0.9995	c. 3 and up
		2. Number of drums (or digits)
0	0.9997	a. 1-3
0.25	0.9993	b. 4-5
0.75	0.9985	c. 7 and up
		3. Style
0.10	0.9995	a. Continuously rotating
0	0.9997	b. Unit jumps
		4. Use
0	0.9999	a. Quantitative read
1.75	0.9990	b. Qualitative read
		5. Numeral legibility
0	0.9999	a. Clear and concise
0.20	0.9994	b. Potentially ambiguous
		6. Exposure (viewing) time
0	0.9999	a. Indefinite
0.20	0.9996	b. 0.08-0.15 sec
0.06	0.9996	c. 0.30-0.75 sec
0.04	0.9999	d. 1.0 sec and up
		7. Recession (Extent to which counter numerals are set back in panel)
0	0.9999	a. Numerals can readily be read from normal operating position
0.25	0.9996	b. Requires movement of operator's head to read numerals
1.00	0.9993	c. Operator must shift body to read numerals

11.218 Differences Between the Natural Optic Array and Display Media

Key Terms

Cinematic displays; CRT displays; display resolution; image quality; information portrayal; optic array; TV displays; video displays; visual simulation

General Description

Differences between the natural optic array (structure of light in the real world produced by the scattering of rays off actual surfaces and substances) and representations via television, CRT displays, and film include light intensity, resolution, and viewer response.

Light intensity In the natural optic array, the intensity differences between adjacent areas can be virtually infinite. A point in the optic array may have a thousand times the photic energy of a neighboring spot. By contrast, with film, the maximum intensity ratio of adjacent areas is probably ~40/1. In video, it is between 10/1 and 20/1. The ratio of a good transparency is ~80/1.

Resolution Resolution on film is determined by properties of the camera, processing, and properties of the film (e.g., grain size). Grain size is less a limiting factor in moving than in still pictures, because details of an object may be constant across several frames.

CRT screen resolution is determined by the size and number of pixels (picture elements). Pixels are separate regions that can be varied independently. Resolution is increased by making the pixels small and close together and having them represent correspondingly small regions in the to-be-displayed scene.

Resolution in TV displays is determined by the number of raster scan lines (usually 512), bandwidth of modulation, focus of beam, and residual glow. Small detail and texture cannot be adequately displayed on television, but closeups can help compensate. Moire patterns and scintillation are TV problems to which there are currently no solutions. Aliasing (jagged edges at an angle to raster) can be alleviated by modulating the edge's intensity.

Other differences include the loss of information from the three-dimensional visual world to a two-dimensional display; the observer's ability to segregate objects (CRef. 11.221); and the eyes' accommodation and convergence activities.

Constraints

- No general measures of image quality are suitable for all purposes. All measures need to be translatable into a statement of the number of points that can be independently varied. Some measures that have been used are **modulation transfer functions** such as **contrast sensitivity** (particularly suited to observation of TV displays), point-spread functions, and line-spread functions.

Key References

*1. Hochberg, J. (1986). Representation of motion and space in video and cinematic displays. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds), *Handbook of perception and human performance: Vol. I. Sensory processes and perception*. New York: Wiley.

2. Hochberg, J., & Brooks, V. (1978). The perception of motion pictures. In E. C. Carterette & M. Friedman (Eds.), *Handbook of perception* (Vol. 10). New York: Academic Press.

3. Millerson, G. (1982). *The technique of lighting for television and motion pictures*. Boston: Focal Press.

4. Roufs, J. A. J., & Bouma, H. (1980). Toward linking perception research and image quality. *Proceedings of the Society for Information Display*, 21, 247-270.

Cross References

11.219 Canonical and non-canonical views: from layout to eye;

11.220 Canonical view: homogeneous and inhomogeneous translation of objects in the field of view;

11.221 Differentiation of targets in TV and cinematic displays

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

11.219 Canonical and Non-Canonical Views: From Layout to Eye

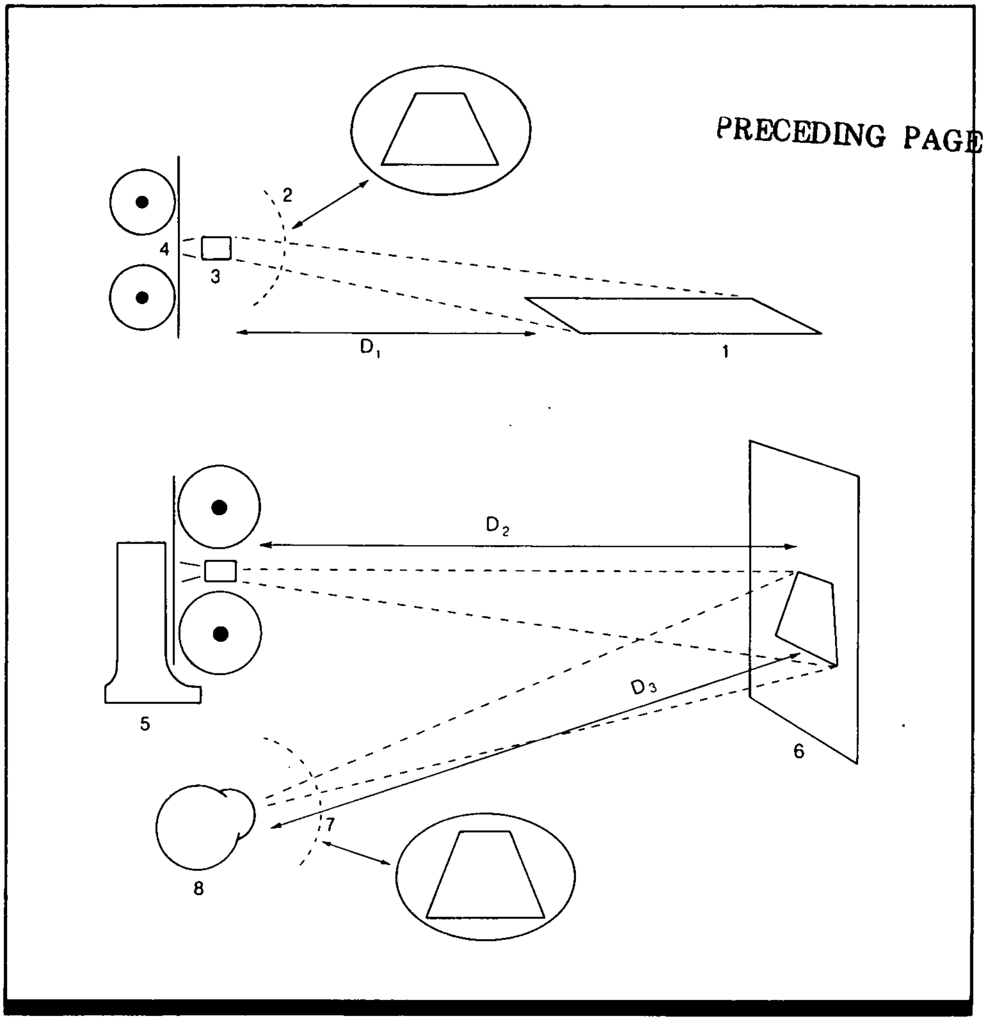

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Figure 1. From layout to eye. (See text for details.) (From Ref. 1)

Key Terms

Binocular disparity; canonical views; cinematic displays; CRT displays; information portrayal; motion parallax; optic array; TV displays; video displays; visual simulation

General Description

With cinematic displays, a *canonical view* is one in which the observer's eye receives the same sheaf of light rays as was received by the camera in filming. The pathway from the layout to the eye is presented in Fig. 1. Ambient light reflected from the scene (1) forms the optic array (2). This is picked up by the projector lens (3) which focuses the image on the film (4) and which is then recorded. The projector (5) casts an enlarged image on the screen (6). Light reflected from the screen forms the optic array (7) which goes to the eye (8) and is the starting point for perception of the motion picture. What the viewer sees, then, depends on the scene itself, characteristics of the camera and projector lenses, recording distance (D_1), projection distance (D_2), and viewing distance (D_3). A canonical arrangement occurs when the optic arrays to the camera and to the viewer are identical, i.e., when (7) and (2) can be superimposed. Many different combinations of the aforementioned variables will produce this effect.

A canonical arrangement in viewing motion pictures, however, is not typical; the situation is normally non-canonical, often due to viewing conditions. First, normal viewing conditions are generally binocular, so that, at best, only one eye will be at the projection center. **Binocular disparity**, then, will specify the distance of the screen to the viewer and the two-dimensionality of the surface (the scene itself is three-dimensional) at a viewing distance of less than ~6 m. Second, the fact that the viewer's head is rarely stationary will also make these conditions apparent to the viewer as a result of **motion parallax** (at any viewing distance). Different head, and therefore eye, positions will also result in different optic arrays. Third, the viewer may be sitting nearer or farther or oblique to the projection center.

Diagrams of different projection arrangements are presented in Fig. 2: (a) shows a layout in space as seen by an observer. The projections, to the eye, of the figure on the screen in (b) to (e) are drawn as viewed from above. The geometry is therefore distorted, but the consequences of dif-

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

ferent arrangements can be seen. Panel (b) depicts a canonical arrangement in which the image of a rectangle viewed at a slant (*i*) is projected to a screen (*ii*) and gives rise to an optic array that fits the rectangle (*i*), the image on the screen (*ii*), and an indefinitely large number of alternative objects (e.g., *iv*, *v*). Two motion vectors (*iii*), parallel and perpendicular to the picture plane, remain equal in projection to the eye. Panel (c) shows an oblique, non-canonical viewing position. The image on the screen (*ii*) no longer fits the rectangle but rather a trapezium (*i*). Also, the angle between the projected images of the unit vectors (*iii*) is not 90 deg. In (d), the image is viewed farther than the canonical position at which the picture was taken (such as with a wide-angle or short lens); the optic array from the screen image fits a rectangle much longer in depth (*i*) than the original. The projected image of the unit motion vector perpendicular to the screen is enlarged relative to the vector parallel to the screen. Panel (e) is a view from nearer to the screen than the canonical position (e.g., a picture taken with a telephoto or close-up lens). Depth is compressed relative to the height and width of the rectangle and the image of the unit motion vector in depth is reduced relative to the vector parallel to the screen.

Other limitations on providing a canonical arrangement include the dimensions and curvature of the screen, the quality and resolution of the film and camera, and the size and shape of the room in which viewing occurs, as well as personal factors such as visual acuity and viewing time. For each viewer there are areas in which distortions are not noticed, areas in which distortions are noticed but tolerated, and areas in which distortions are not tolerated. Lines of iso-deformation (where apparent distortions are equal) can be computed (Ref. 3).

Acceptable viewing distances can also be decomposed into horizontal and vertical sectors (Ref. 2). For the horizontal component, when viewing occurs at an oblique angle, visual fatigue may result from prolonged viewing due to compensatory head movements and postural orientation different from the direction of gaze. Orienting seats toward the screen may help this. For vertical viewing angles, the optimum sight line is a very slight angle of depression (~5 deg) below the perpendicular axis.

Applications

Film and video displays; designing viewing rooms, visual simulation determining minimal standards for equipment quality.

Key References

*1. Hochberg, J. (1986). Representation of motion and space in video and cinematic displays. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I. Sensory processes and perception*. New York: Wiley.

2. McVey, G. F. (1970). Television: Some viewer-display considerations. *Audio-Visual Communications Review, 18*, 277-290.

3. Meister, R. (1966). The iso-deformation of images and the criterion for delineation of the usable areas in cine-auditoriums. *Journal of the Society of Motion Picture and Television Engineers, 75*, 179-182.

4. Rosinski, R. R., & Farber, J. (1980). Compensation for viewing point in the perception of pictured space. In M.A. Hagen (Ed.), *The perception of pictures* (Vol. 1). New York: Academic Press.

Cross References

5.902 Motion parallax;

5.916 Perceived depth as a function of lateral retinal image disparity;

11.218 Differences between the natural optic array and display media;

11.220 Canonical view: homogeneous and inhomogeneous translation of objects in the field of view;

11.221 Differentiation of targets in TV and cinematic displays

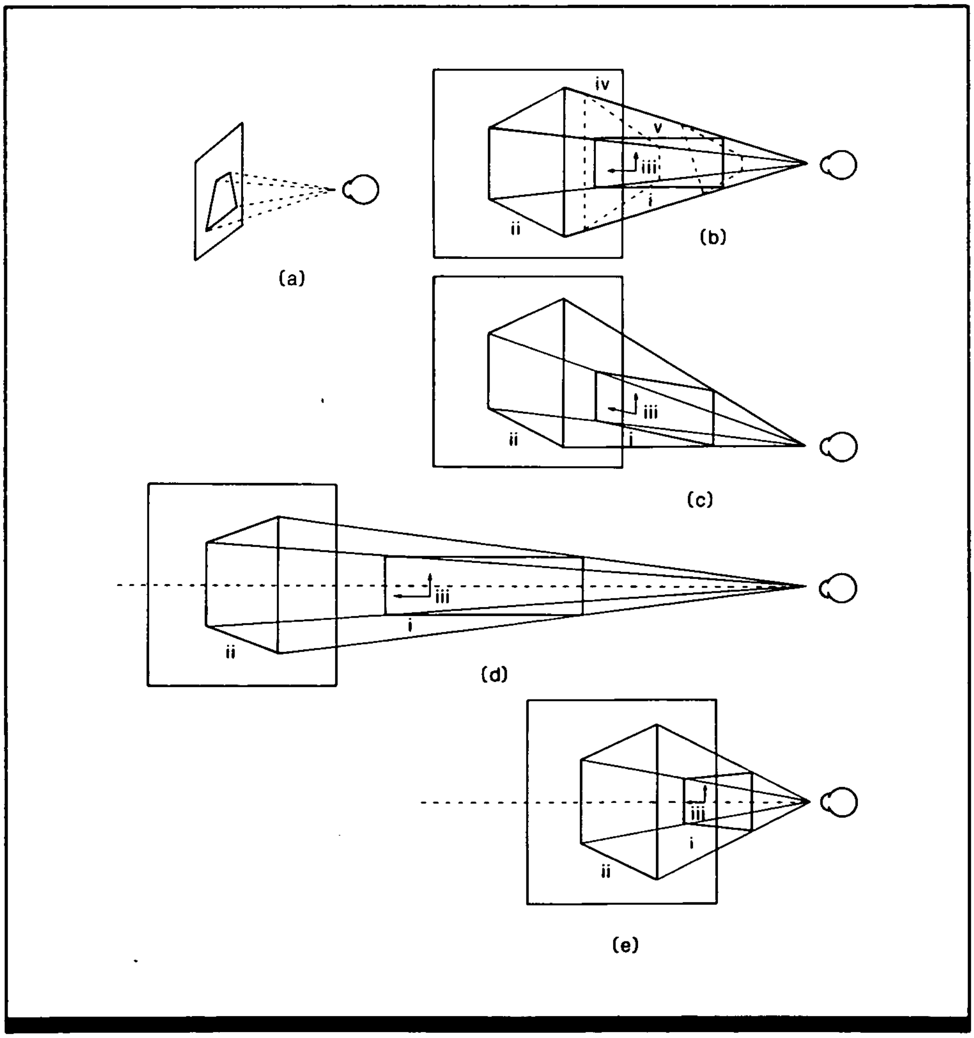

Figure 2. Distortions resulting from departures from canonical arrangement. (See text for details.) (From Ref. 1)

11.220 Canonical View: Homogeneous and Inhomogeneous Translation of Objects in the Field of View

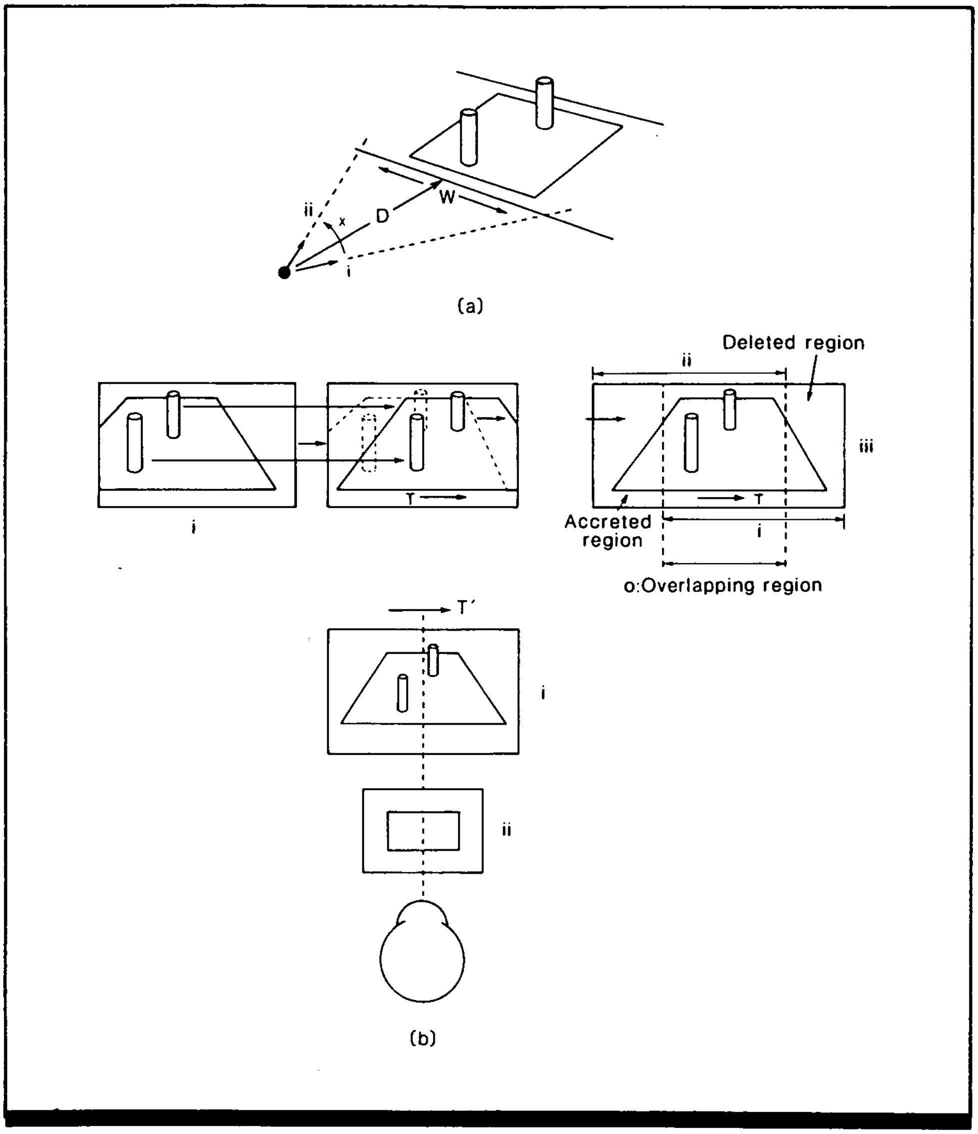

Figure 1. Movement around the optical node of the eye or camera. (See text for details.) (From Ref. 1)

Key Terms

Canonical views; cinematic displays, CRT displays; field of view; image rotation; image translation; information portrayal; optic array; TV displays; video displays; visual simulation

General Description

In a canonical arrangement [one in which the eye and the camera receive the same sheaf of light rays (CRef. 11.219)], when the eye or the camera rotates, the retinal and motion picture images undergo either homogeneous or inhomogeneous translation. Which sort of translation occurs depends on the ratio of the viewing distance (*D*) to the width (*W*) of the field of view. Homogeneous translation occurs when *W*/*D* is small; inhomogeneous translation occurs when *W*/*D* is large.

Homogeneous Translation: In homogeneous translation, each point in the image undergoes a uniform transformation so that relative spatial relationships within the image remain invariant, as shown in Fig. 1. In Fig. 1a, when the eye or camera is rotated from (*i*) to (*ii*) through angle *x*, each point is translated by the vector **T**. As generally occurs, the whole scene is larger than the field of view (*D* is large compared to *x*). In this case, the translation is accompanied by an accretion and deletion of elements at the margins of the retinal image or projection screen. In the overlapping section of the field (*o*), spatial relationships remain invariant.

Objects at different distances, in homogeneous translation, are translated approximately equally; there is no motion parallax, motion perspective, or kinetic occlusion within the image. One consequence of this is that the transformation depicted in Fig. 1a represents either of two events equally well. The first is the translation of a three-dimensional display with relative motion, vector **T**. This will result from a rotation (x) of the lens around its node or the orbiting of the display itself around the node, or some combination of these. The second is the translation of a two-dimensional display across the field of view by vector **T** (Fig. 1b). In this case, the uniformity of the translation vector will specify a flat surface at some distance and velocity relative to the viewer as determined by some scaling factor.

Inhomogeneous Translation: Inhomogeneous translation, which occurs with a large W/D ratio, is depicted in Fig. 2. Different picture projections will result from a fence made of pipes or cylinders, *i* in Fig. 2a, and a fence made of slats or flat boards, *ii* in Fig. 2a, depending upon the type of camera motion and departures from a canonical arrangement. Given some distance D, the picture that gives rise to the same optic array as the uniform pipe fence, *i* in Fig. 2b, is nonuniform, *ii* in Fig. 2b, over the width, W, of the picture because the circularity of the pipes presents the same tangent to the line of sight at all eccentricities and the projected images increase in width with increasing eccentricity. The flat fence, *iii* in Fig. 2b, however, provides a uniform picture, *iv* in Fig. 2b. With the flat slats, the decrease in visual angle of the target with eccentricity is compensated for by the concurrent increase in obliqueness of the film plane. (The occurrence of this phenomenon in still pictures is discussed in Ref. 2.) The "distortion" in Fig. 2b *ii* can be avoided by keeping a low W/D ratio.

The effects of a pan shot, in which the eye or camera rotates, are shown in Fig. 2c and 2d. With the pipe fence (Fig. 2c), when the viewer's gaze tracks from the nearest post (1) to the farthest (5), the picture that is perpendicular to the line of sight, and provides the same optic array as the fence, changes from P_i to P_{ii}; in neither picture are the contours uniformly spaced. With the slat fence (Fig. 2d), the contours in the picture are uniformly spaced as long as the picture plane and the fence are parallel (P_i); the spacing departs from uniformity as the gaze pans to center on slat 5, and the picture plane is at some angle to the fence.

The effects of track shots are depicted in Fig. 2e and 2f. With the pipe fence, Fig. 2e, a lateral displacement of the camera from (*i*) to (*ii*) changes the skew of the pictures, P_i and P_{ii}. With the slat fence, Fig. 2f, displacing the camera from (*i*) to (*ii*) leaves the pictures uniform and unskewed.

In sum, then, when W/D is large, the succession of retinal or projection images is very different for rotation than for translation. However, as long as a canonical arrangement is maintained, and the viewer's (monocular) eye is at the projection center, the optic array is the same from the pictures as from the scene itself.

Key References

*1. Hochberg, J. (1986). Representation of motion and space in video and cinematic displays. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I. Sensory processes and perception*. New York: Wiley.

2. Pirenne, M. (1970). *Optics, painting and photography*. Cambridge, England: Cambridge University Press.

Cross References

11.218 Differences between the natural optic array and display media;

11.219 Canonical and non-canonical views: from layout to eye;

11.221 Differentiation of targets in TV and cinematic displays

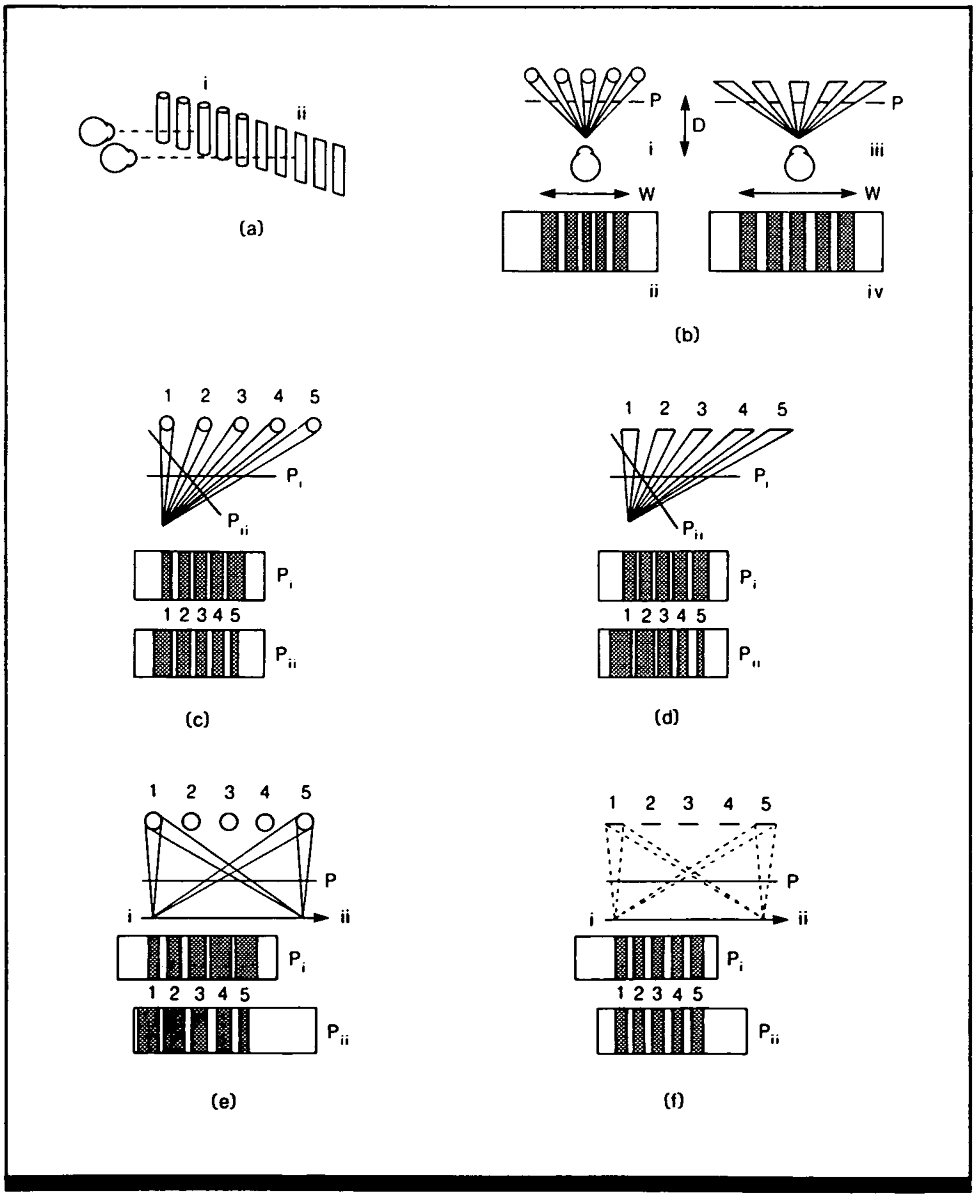

Figure 2. The projection of a pipe or slat fence. (See text for details.) (From Ref. 1)

11.221 Differentiation of Targets in TV and Cinematic Displays

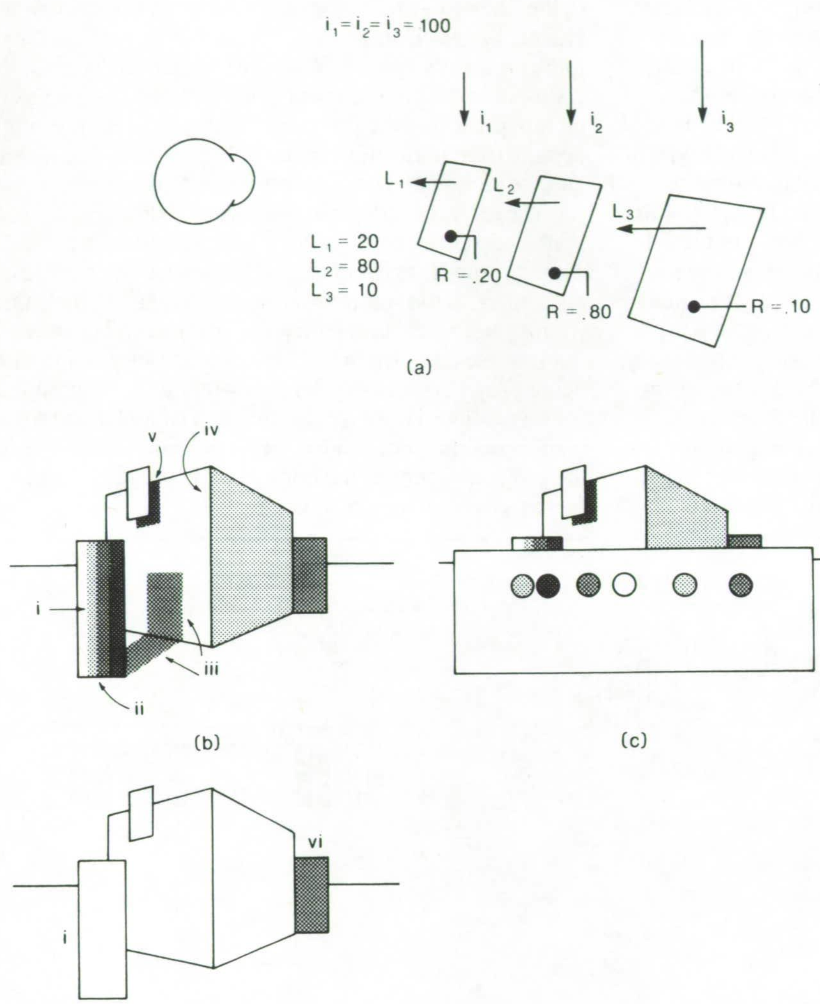

Figure 1. Reflectance and illumination. (See text for details.) (From Ref. 4)

Key Terms

Cinematic displays; field of view; information portrayal; scene analysis; target acquisition; TV displays; video displays; visual simulation

General Description

Object constancy is the real-world visual phenomenon in which characteristics of objects remain approximately constant even though viewing conditions change. To correctly segment the visual world into its constituent parts, the observer must perceive an object's permanent properties (for example, an object's reflectance, the percentage of light energy reflected from that surface), regardless of the amount of illumination at a particular time. In a film or other artificial visual display, the factors that help observers distinguish one object from another include hue, **luminance**, size of field of view, and motion.

Colored images have an obvious advantage: regions can be identified as belonging together on the basis of common hue. In static displays, however, hue alone is not sufficient; luminance differences are also necessary for proper object segregation. This limitation is apparent under conditions of diffuse illumination which eliminates shadows at object boundaries.

Figure 1 illustrates the relation between reflectance and luminance. Part (a) shows a set of surfaces that receive the same illumination ($i_1 = i_2 = i_3$) and that are oriented at the same angle to the camera. In this case, the luminances (L_1, L_2, L_3) of the surfaces are proportional to, and give information about, their reflectances (R). In this case, pixels of equal lightness and hue in the image will be likely to represent homogeneous regions in the real world.

In general, however, surfaces are neither uniformly illuminated nor at the same orientation to the camera or the source of the illumination (Fig. 1b, 1c, 1d). In this case, identical reflectance need not correspond to identical color, and vice versa. In Fig. 1b, luminance changes are indicated by changes in incidence and reflection angle (cylinder *i*, corner *iv*) and also by shadows either at a distance (*iii*) or at the edges of the object (*v*). These changes provide information about spatial form and layout. If a reduction screen is used to remove contextual information (Fig. 1c), then the luminance differences between regions are revealed.

The same layout can also be illuminated by diffuse light (Fig. 1d). In this case, much information is lost. For example, the cylinder (*i*) may be indistinguishable from a picture of a rectangle. However, local luminance will be a more reliable index of reflectance (e.g., region *vi* is perceived as darker than adjacent regions).

Figure 2 shows the influence of viewing angle on object segregation. With a wide angle (Fig. 2a), spatial arrangement can be established through the context, which clarifies the relation between reflectance and luminance. Contextual information is reduced as the angle narrows (Fig. 2b). With a smaller angle (Fig. 2c) as in a close-up view, there may be no contextual information by which to separate luminance from reflectance. In this case, the fact that the background wall and the person are equally light (Fig. 2a) can no longer be perceived.

Close-ups can, however, given adequate depth of field, provide additional information about surface texture. Texture can help separate luminance from reflectance: (1) since textured surfaces produce highlights, information about illumination is provided, and (2) textured surfaces provide slant information through texture-density gradients to the line of sight and direction of illumination. The close-up acts somewhat like the reduction screen in Fig. 2c.

In film, when the camera moves relative to a stationary background, much of the information for the correct scene segmentation found in natural vision is preserved. This is especially true for a wide field of vision and high resolution. When an object moves (e.g., Fig. 1b *iii*), the shadow will move relative to the background, marking a change in illumination and not reflectance.

Object constancy will be particularly impaired in situations in which there is a narrow field of view, with low illumination (obscuring the diffraction pattern of the penumbra of a shadow) or with limited information about the object's orientation with respect to the direction of illumination.

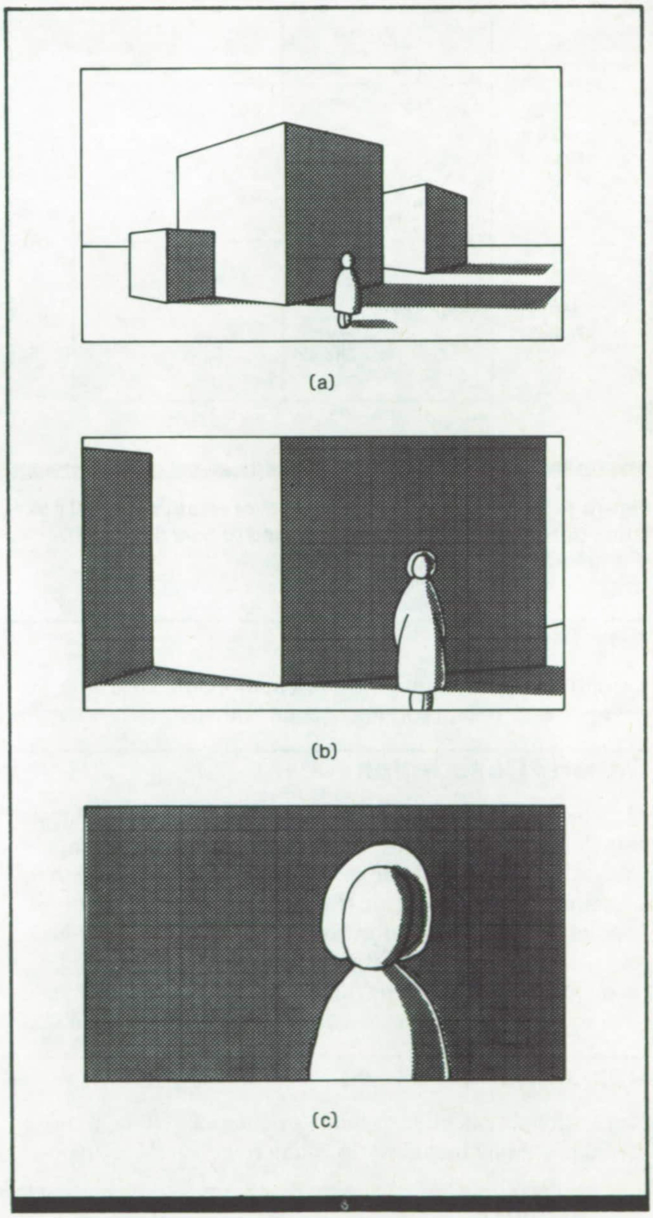

Figure 2. Different angles of view. (See text for details.) (From Ref. 4)

Key References

1. Bishop, H. P. (1966). Separation thresholds for bar targets presented with color contrast only. *Psychonomic Science, 6*, 293-294.

2. Hochberg, J. (1979). Sensation and perception. In E. Hearst (Ed.), *The first century of experimental psychology*. Hillsdale, NJ: Erlbaum.

3. Hochberg, J. (1980). Pictorial functions and perceptual structures. In M. Hagen (Ed.), *The perception of pictures* (Vol. 2). New York: Academic Press.

4. Hochberg, J. (1986). Representation of motion and space in video and cinematic displays. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance: Vol. I. Sensory processes and perception*. New York: Wiley.

Cross References

5.221 Decomposition of composite motion;

11.218 Differences between the natural optic array and display media;

11.219 Canonical and non-canonical views: from layout to eye;

11.220 Canonical view: homogeneous and inhomogeneous translation of objects in the field of view

11.222 Map Learning

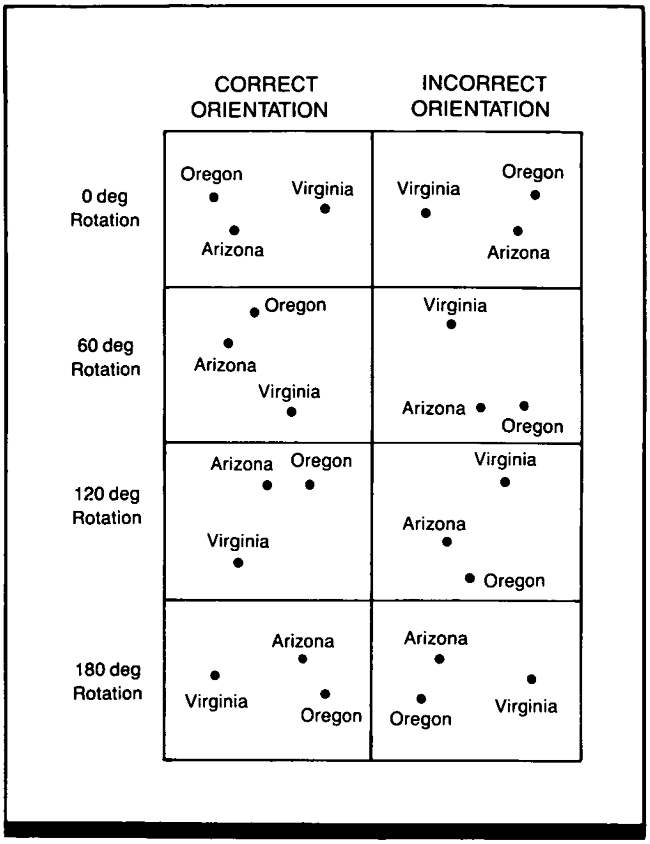

Figure 1. State triads for judgments of relative spatial position (interpoint distances are scaled to true distance). (From Ref. 1)

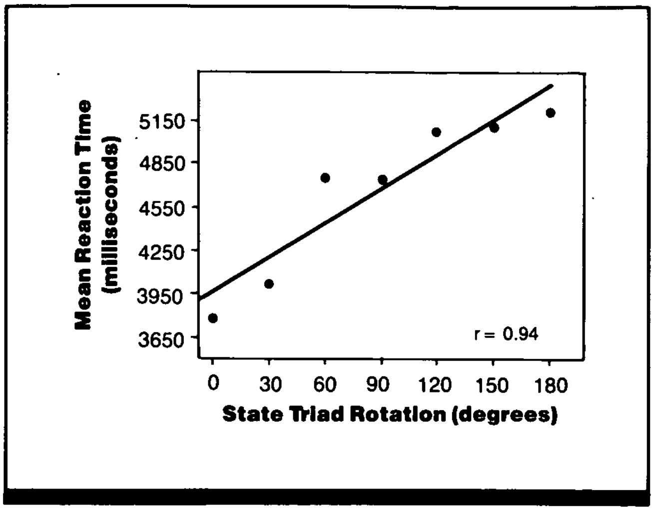

Figure 2. Mean time for correct judgments of relative spatial position of state triads as a function of angular displacement of triad orientation from standard map orientation. (From Ref. 1)

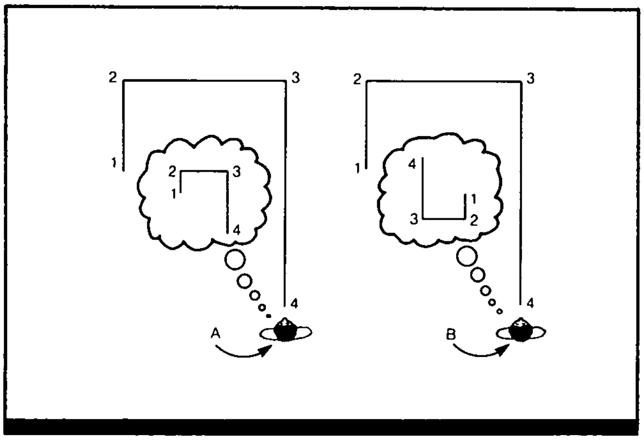

Figure 3. Subject A facing a route with a cognitive map that is aligned with the route; subject B facing a route with a cognitive map that is 180 deg misaligned with the route. (From Ref. 2)

Key Terms

Cognitive maps; geographical orientation; map learning; navigation; problem solving; spatial knowledge

General Description

Map-like representations (cognitive maps) of geographical knowledge can be acquired from studying maps or from navigating routes. Either experience allows triangulation in a Euclidean distance metric (i.e., locating point C relative to point A, given only information about the location of C relative to point B and of B relative to A). Map-learning produces a cognitive map with a fixed orientation; this leads to slower, more error-prone navigation when individuals' cognitive maps are not aligned with their present situation. Extensive navigational experience produces a cognitive map that is essentially orientation-free and has better route distance information than that produced by map-learning.

Applications

Navigational errors due to faulty orientation will be minimized if training includes traversing routes in the map domain. You-are-here maps presented vertically will be most easily read if the horizontal-forward direction corresponds to moving up on the map.

Constraints

- Route learning has only been studied for relatively confined regions with well-defined boundaries (e.g., a room, a building, a campus) and may not be as effective over more extended spaces (Ref. 3).
- Pre-experimental experience with tested routes has not been controlled.
- Effects of studying maps in different orientations is not known.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Summary of data on properties of spatial representations in memory for judgments of distance and orientation.

Methods	Results	Source
Distance Judgments		
Undergraduates judged relative interpair distances for pairs of states (n = 10) or buildings on their campus (n = 11); ten pairs with interpair distance ratios of 0.04-0.94 tested twice in all 45 possible combinations of one pair against every other; subjects saw one pair for 4 sec followed by a second pair and then presses one of two response keys to indicate if the first or second pair represented shorter distance	Mean reaction time for correct distance judgments increased linearly with interpair distance, with $r = 0.74$ for campus buildings and $r = 0.83$ for states.	Ref. 1 (Exp. 1)
Female undergraduates (n = 24) who learned from a map and female secretaries (n = 24) who learned from navigation estimated Euclidean and route distances for seven locations within a building	Map learners showed equally good spatial knowledge for relations among locations (r's >0.80 between true and estimated distances), with higher absolute errors (36%) for route than for Euclidean (33%) distance; route learners had better spatial knowledge of relations among locations $r = 0.88$) and lower absolute errors (26%) for route than for Euclidean distances. Route experience diminishes the difference between route and Euclidean knowledge.	Ref. 4
Orientation Judgments		
Undergraduates judged whether three map locations of states or of campus buildings were in correct spatial relation to each other (Fig. 1); five sets of triads for states and five for buildings tested at seven orientations from 0-180 deg in 30-deg steps, for 70 trials at a 6-sec intertrial interval; subjects pressed one of two keys to indicate if triad was or was not in correct spatial relation; 10 subjects judged buildings from own campuws and 10 judged buildings from an unfamiliar campus, learned from a map.	Mean correct response time increased as a linear function ($r = 0.94$) of angular difference between orientation of test triad and orientation of standard map for knowledge learned from maps (Fig. 2), but not for knowledge based on navigational experience.	Ref. 1 (Exps. 2, 3)
Undergraduates (n = 16) learned a five-point path of four line segments (lengths = 0.8-3.5 m) by walking it blindfolded three times, then were stationed at one location and told to walk to and mark a second point on the path while blindfolded.	Ability to traverse a shortcut between two points was as good as ability to traverse a learned path.	Ref. 2 (Exp. 3)
Undergraduates learned a four-point path of three line segments (lengths = 0.8-3.5 m) either by viewing (n = 24) or by tracing with their finger while blindfolded (n = 32) a scaled map of the path, then were stationed at second point; test was either aligned with the training map (Fig. 3a) or was misaligned (Fig. 3b).	23-30% of those tested with a misaligned map made orientation errors >90 deg, thus walking away from the destination (Fig. 4).	Ref. 2 (Exps. 4, 5)

Key References

*1. Evans, G. W., & Pezdek, K. (1980). Cognitive mapping: Knowledge of real-world distance and location information. *Journal of Experimental Psychology: Human Learning and Memory, 6*, 13-24.

*2. Levine, M., Jankovic, I. N., & Palij, M. (1982). Principles of spatial problem solving. *Journal of Experimental Psychology: General, 111*, 157-175.

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*4. Thorndyke, P. W., & Hayes-Roth, B. (1982). Differences in spatial knowledge acquired from maps and navigation. *Cognitive Psychology, 14*, 560-589.

Cross References

4.104 Skilled memory effect;

4.107 Cognitive mapping of the environment;

6.315 Mental rotation of objects;

11.223 Design of "you-are-here" maps;

Handbook of perception and human performance, Ch. 28, Sect. 3.4

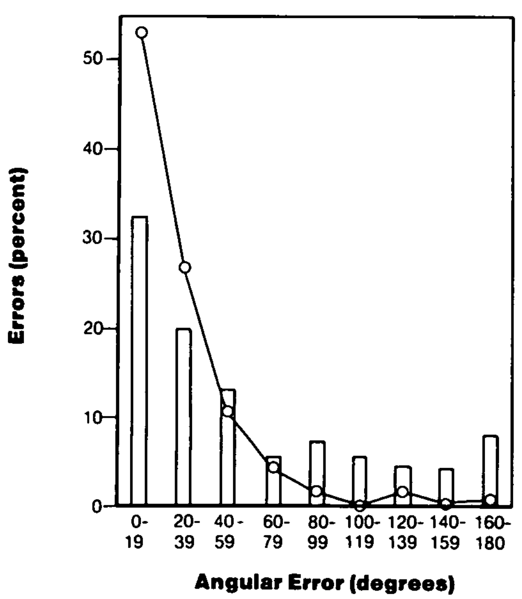

Figure 4. Angular errors of route traversal for subjects in Exps. 4 and 5 of Ref. 2. The circles depict results for subjects with aligned maps (note that over half of the errors were under 20 deg) and the bars depict data for subject with misaligned maps (note the high frequency of errors of 80 deg and greater). (From Ref. 2)

11.223 Design of "You-Are-Here" Maps

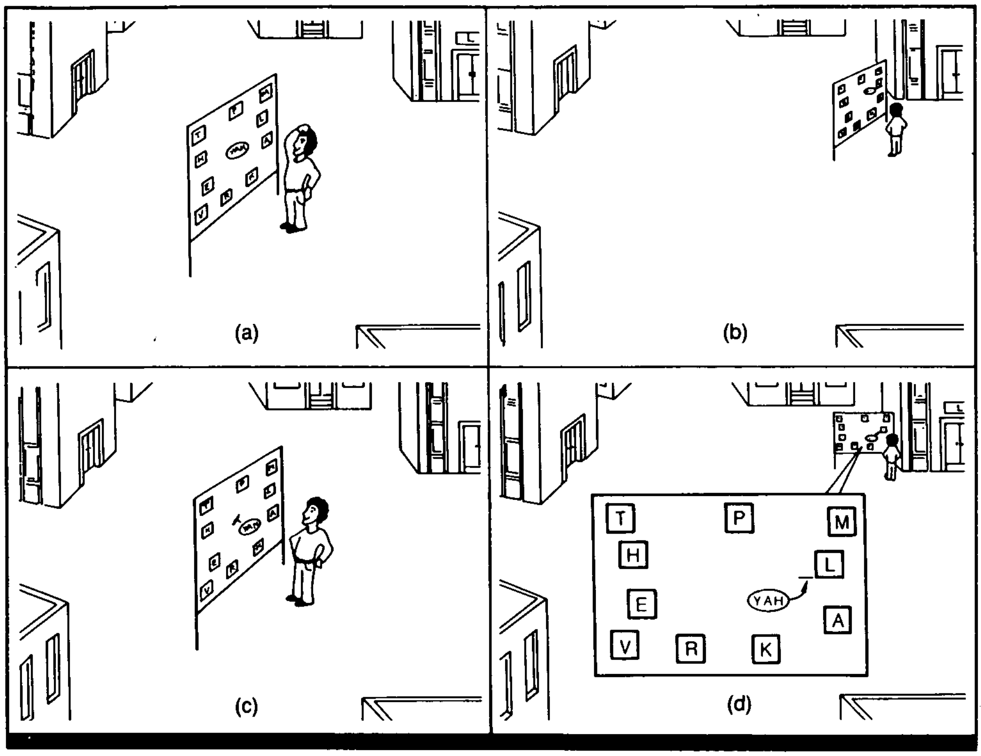

Figure 1. Four examples of how the information needed to apply the two-point theorem and establish the correspondence between map and terrain can be used in you-are-here maps: (a) features of the terrain can be labeled, with labels noted on the map; (b) map can be placed asymmetrically near a salient terrain feature; (c) placement of both map and map reader can be symbolized on the map; and (d) all three principles can be combined. (From M. Levine, You-are-here maps: Psychological considerations, *Environment and Behavior*, *14*, 221-237. Copyright 1982. Reprinted by permission of Sage Publications, Inc)

Key Terms

Alignment principle; cognitive maps; forward-up equivalence principle; map reading; navigation; spatial knowledge

General Description

Laboratory and field studies (Refs. 1-4) have determined several psychological principles important to good design of "you-are-here" maps. The most important findings are expressed in the two-point theorem, the alignment principle, and the principle of forward-up equivalence.

Two-Point Theorem

To use a map of a terrain, the map user must be able to relate two points on the map to two locations in the terrain, or relate one point and a direction on the map to a point and a direction on the terrain. Identifying the map's location on a you-are-here map provides one pair of corresponding points. The additional point or direction needed to read the map can be provided in various ways (Fig. 1): features in terrain can be labeled (e.g., building L); map can be placed, asymmetrically, near an identifiable terrain feature; location of both the map and the map reader can by symbolized; or all of these possibilities can be combined to provide redundant two-point information.

Alignment Principle

A map should be aligned with the terrain. On a horizontally placed map, the direction between any pair of locations in the terrain should be parallel to the direction connecting the map symbols for those locations. For example, when facing a correctly aligned, horizontal map which depicts a river on the left side and a mountain on the right, map readers will know that in the terrain there is a river to the left and a mountain to the right, relative to the map reader's present position.

Forward-Up Equivalence Principle

The upward direction of a map in a vertical position is equivalent to the forward direction of a map in a horizontal position. A vertical map is properly aligned when a 90-deg rotation from vertical to horizontal yields a properly aligned horizontal map (Fig.2).

Failure to comply with these principles produces counteraligned maps that are hard to read and likely to produce significant map-reading errors (e.g., going off in the direction opposite the desired one). A common design problem is placement of a map on the wrong wall (Fig. 3).

Empirical Validation

The three principles for good design of you-are-here maps have been experimentally validated. Subjects made significantly fewer errors and response times were much shorter when subject's cognitive map was in accordance with the design elements. Experimental conditions included blindfolded subjects walking a rectangular path on the floor of a room, subjects finding an office in a large office building, and subjects marking on a picture the path to a building specified on a map. In a real-world situation, a hospital had to move floor maps to an opposite wall because people kept getting lost; the new positions of the maps conformed to these design principles.

Key References

*1. Levine, M. (1982). *Cognitive maps and you-are-here maps.* Paper presented at the meeting of the American Psychological Association, Washington, DC, August, 1982.

*2. Levine, M. (1982). You-are-here maps: Psychological considerations. *Environment and Behavior, 14,* 221-237.

3. Levine, M., Jankovic, I., & Palij, M. (1982). Principles of spatial problem solving. *Journal of Experimental Psychology: General, 111,* 157-175.

*4. Levine, M., Marchon, I., & Hanley, G. (1984). The placement and misplacement of you-are-here maps. *Environment and Behavior, 16,* 139-157.

Cross References

4.107 Cognitive mapping of the environment;

6.315 Mental rotation of objects;

11.222 Map learning;

11.403 Target coding: effect on search time;

Handbook of perception and human performance Ch. 28, Sect 3.4

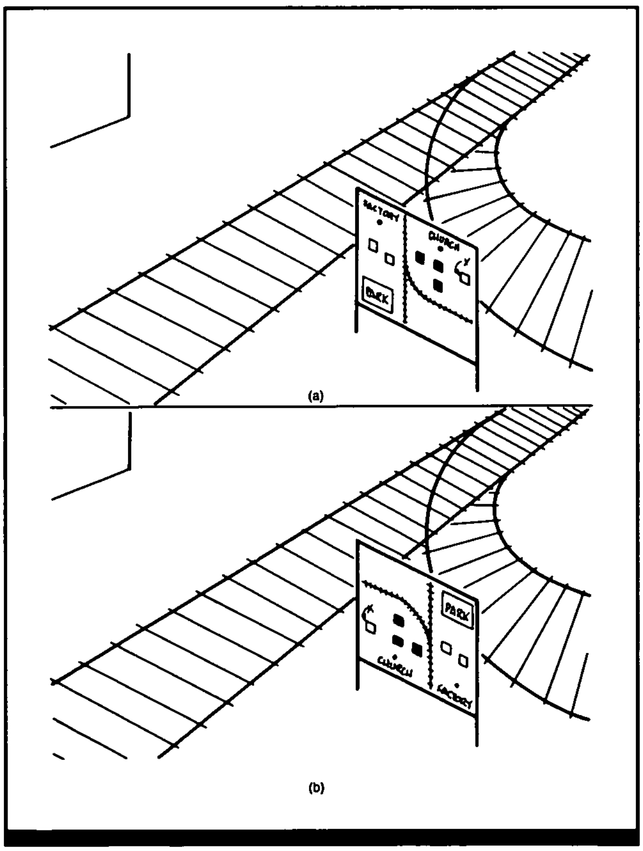

Figure 2. Illustration of the principle of forward-up equivalence; the vertical map in (a) is properly aligned with the terrain; the map in (b) is not. (From Ref. 1)

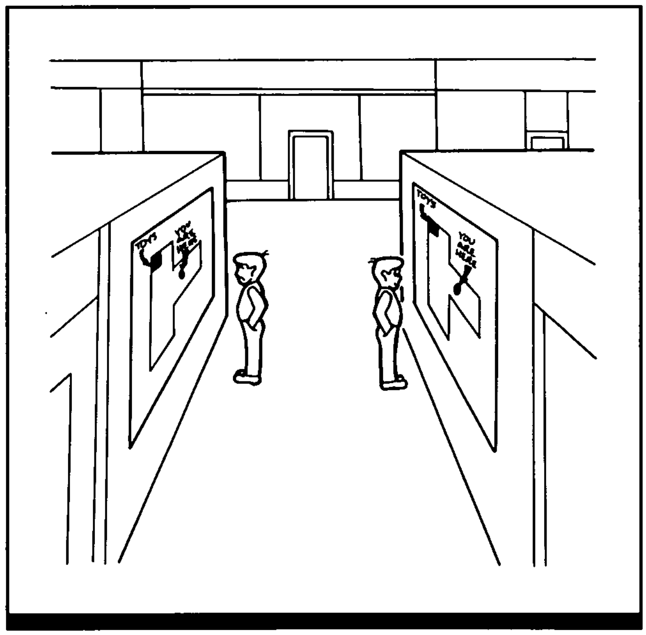

Figure 3. Two identical wall-mounted maps, illustrating how placement on one wall (in this case the lefthand wall) can produce a counteraligned map whereas placement on the opposite wall (in this case the righthand wall) produces a properly aligned map. (From M. Levine, I. Marchon, & G. Hanley, The placement and misplacement of you-are-here maps, *Environment and Behavior, 16,* 139-157. Copyright © 1984. Reprinted by permission of Sage Publications, Inc)

11.301 Steps in Dialogue Design

Key Terms

Dialogue design; person-computer dialogue

General Description

Figure 1 displays a systematic sequence of analyses for the design of a person-computer dialogue. In such a system, the user typically provides the greatest variability of any system component. The design of a successful dialogue-based system relies heavily on thorough systematic analyses from which the needs, characteristics, and capabilities of all system components, including the human, can be understood and integrated into a successful design.

Analyses to determine the types and characteristics of all potential users must be carefully conducted. Imperfect design requirements result from assuming that the designer already knows the characteristics of the user. Steps 2 through 5 address the types of system users, their role in the system, and the users' capabilities.

System hardware/software requirements can be established only with full knowledge of user characteristics. Steps 7 through 11, including their requisite feedback loops, provide the opportunity to match the hardware and software with the needs and capabilities of the user groups. These steps should include the human factors considerations of the hardware (e.g., operator comfort, workspace layout, and illumination/CRT glare), as well as system response time and operator workload.

Steps 12 through 16 involve the design of the initial dialogue structure and error and failure control procedures. Step 17 represents a critical design step: necessary dialogue simulation experiments prior to actual coding of the dialogue software (Steps 18-20). Participation of the future system users at all levels provides valuable feedback to the designers regarding the acceptability of the dialogue to the users. Furthermore, user involvement at this phase can "build in" a sense of commitment to the new system, easing potential negative acceptance when the system becomes operational.

"Bullet-proofing," the final step (Step 21), is an attempt to design "safety" features to protect the system from tampering due to experimentation, boredom, confusion, or misunderstanding of the system or dialogue. It may even be malicious and deliberate. This tampering can, in some cases, be predicted, given a complete understanding of the user groups. Other potential problems, as well as solutions to them, can be identified in simulation/system trials with representative *users*. It is critical that these trials be performed with representative users, not system engineers, programmers, etc. No matter how open-minded the system designer, only a representative user can be expected to react like a real system user.

Applications

Development of new systems that include person-computer dialogue; troubleshooting of existing dialogue that is not achieving performance or acceptance standards.

Constraints

- Applicability of specific steps may vary with system type or needs.

Key References

1. Hendricks, D., Kilduff, P., Brooks, P., Marshak, R., & Doyle, B. (1982). *Human engineering guidelines for management information systems.* Alexandria, VA: U. S. Army Materiel Development and Readiness Command.

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Cross References

11.302 Basic properties of person-computer dialogue;

11.303 Comparison of approaches to person-computer dialogue

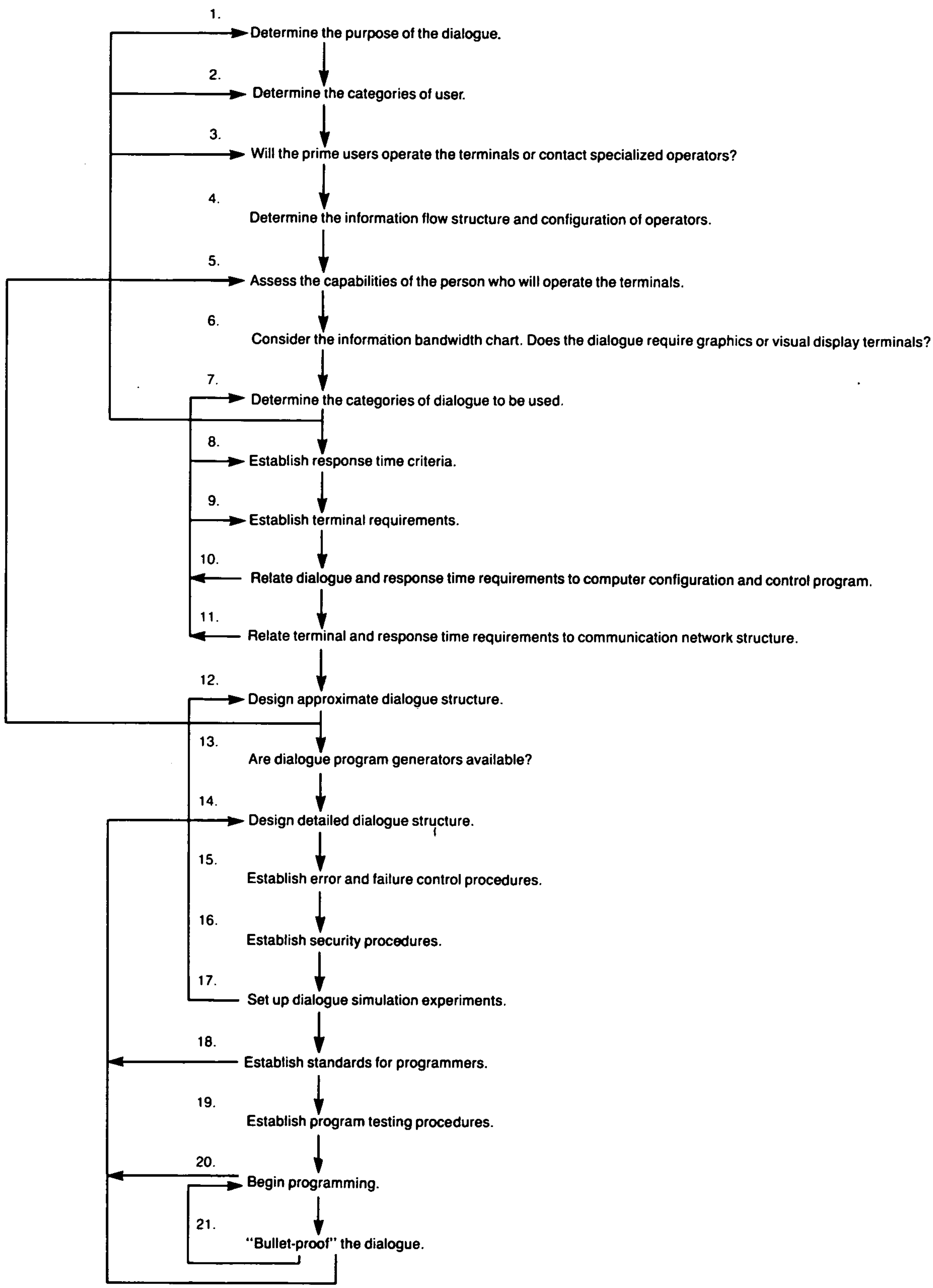

Figure 1. Possible steps in dialogue design. (From James Martin, *Design of man-computer dialogues*, Copyright © 1973, pp. 10, 12-13, 34. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.)

11.302 Basic Properties of Person-Computer Dialogue

Table 1. Basic dialogue properties and considerations. (From Ref. 10)

Property	Design Considerations	Sources
A. Initiative	*Computer Initiated:*	
	For naive or casual users	Refs. 6, 7, 12, 13
	Relies on passive rather than active vocabulary	
	Can teach a "system model" to unfamiliar users	
	Satisfactory for experienced users if system response is fast	
	Can constrain the amount of information in a transaction	
	User Initiated:	
	For experienced users	
	For frequently used actions or rapid interchanges	
B. Flexibility	High Flexibility	
	For experienced/sophisticated users	Refs. 4, 11, 15, 16
	Increases error rate of inexperienced users	
	Results in use of known problem-solving solutions rather than unlearned alternatives that are less cumbersome	
C. Complexity	Optimal level is a function of task and user type	Refs 1, 2, 3
	Deviation from optimal complexity results in degraded performance	
	Redundant or irrelevant commands impair performance	
D. Power	Must correspond to user's needs, which may change over time	Refs. 4, 11, 17
	System generality decreases with use of powerful (rather than less powerful) basic commands	
	Powerful commands (in conjunction with basic commands) increase complexity	
E. Information Load	Performance degrades if load is too high or too low	Refs. 5, 8, 10, 14
	Load can be empirically measured or estimated	
	Load is a major success factor, but not often a formal design consideration	

Key Terms

Information load; interactive systems; mixed initiative dialogues; person-computer dialogue

General Description

All person-computer dialogues involve five major characteristics (Table 1).

(A) The dialogue is "computer-initiated" if the computer asks questions, presents alternatives, etc., and the user responds. If the user inputs commands without such computer "prompting," the dialogue is "user-initiated." Combinations of computer- and user-initiated dialogues are also possible and may be useful in situations involving varied user types. In "variable-initiative" dialogues, either the user or the computer selects the type of dialogue (either computer-initiated or user-initiated). In "mixed-initiative" dialogues, either the user or the computer may take the initiative.

(B) Flexibility is a measure of the number of ways in which a user can accomplish a given function. High flexibility can be achieved by providing a large number of commands, by allowing the user to define or redefine commands, etc.

(C) Complexity, which is related to flexibility, is a measure of the number of options available to the user *at a given point* in the dialogue. Low complexity can be achieved by using few commands, or by partitioning the commands so that the user selects from a small set at any given time.

(D) Power, which is related to both flexibility and complexity, is the amount of work accomplished by the system in response to a single user command. In a dialogue with powerful commands, one command may accomplish an operation that would require several in a system with less powerful commands.

(E) Information load is a measure of the degree to which the interaction absorbs the memory and/or processing resources of the user.

Constraints

- Selection of initiative mode must consider dialogue structure and transaction content, in addition to user types and system response time.
- Flexibility is difficult to measure in existing dialogue design.
- Complexity, as defined here, describes cognitive complexity at dialogue decision modes, not structural complexity.
- No clear guidance on optimal complexity exists in the literature.
- No standard metric or dialogue power exists.
- Measurement of workload and information load may be a problem.

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Cross References

11.301 Steps in dialogue design

11.303 Comparison of Approaches to Person-Computer Dialogue

Table 1. Comparison of interactive dialogues.

Type of Dialogue	Advantages	Disadvantages
Programming languages	Concise, precise, powerful, flexible	Inappropriate for the vast number of terminal users who have not learned to program and do not want to (e.g., management, general public, administrative staff)
English-language dialogue	Theoretically, the most natural man-machine interface	Unsuitable where an operator's input must be interpreted with precision (because of ambiguity). Sometimes satisfactory for computer-assisted instruction, but should be avoided on commercial applications; there are immense software problems
Limited English input	Users employ familiar words	Some users tend to overestimate the intelligence of the machine and overstep the tight restrictions on input wording
Question and answer (in which the computer asks the operator a series of questions)	Very simple for the operator; can be written with a simple program	Of limited flexibility; suitable for certain applications only
Mnemonics	Can be concise and precise (e.g., airline reservation dialogue)	Operator must be familiar with mnemonics and formats
Programming-like statements	Can be concise and precise	Operator must be well trained, familiar with the coding, and have limited programming aptitude
Computer-initiated (in which the operator responds to the computer rather than the computer responding to the operator)	The computer tells the operator what to do; little training required; can be used with a totally untrained operator	Dialogue can be lengthy and often slow. Many characters; high line use; more expensive networks; little flexibility in sequence of operation
Form-filling (in which the operator fills out a "form" on a visual display)	Straightforward for operator except for cursor manipulations	Less flexible than a "branching tree" of questions, and error correction procedures are less easy
Menu selection	Simple for the operator; can be written with a simple program generator	Limited in scope; large number of characters used; more expensive telecommunication network
Build dialogue features into special terminal hardware	The intent is usually to clarify and simplify the operator actions. A similar effect could often be achieved without special hardware, however	Expensive; inflexible; may restrict future development
Light-pen input (or other means of pointing to the screen)	Simple form of input, ideal for an untrained operator; can speed up a complex dialogue	Limited in scope unless a keyboard is used as well as the light pen
Fixed-panel responses (in which the computer responds with one of a standard set of panels)	Simple for programming; panels can be stored in devices away from the main computer, giving low transmission requirements; in some cases, panels with pictures may be used	Inflexible; of limited scope
Modified-panel (in which the panels can be modified by the programs)	Can also save transmission requirements; simpler than three-form dialogues	Loses the simplicity of fixed-panel dialogues
Graphics using chart displays	Very effective for summarizing information and manipulating models; ideal for many dialogues with management	Expensive; elaborate programming requirements (which may be available through software); on tele-processing systems "intelligent" terminals are needed to avoid bandwidth restraints
Graphics using symbol manipulation	Very effective for complex problem solving, engineering design, etc.	Expensive; elaborate programming requirements; needs "intelligent" terminals

Type of Dialogue	Advantages	Disadvantages
Photographic frames	Photographs are valuable in certain applications (e.g., real estate, personnel, engineering, parts, systems used by children); they may become extensively used when home CATV terminals come into use	Telecommunication channels in use, other than CATV, have insufficient bandwidth for photograph transmission. The images must therefore be stored at the terminal location
Voice answerback	The telephone is the cheapest available terminal	Limited in what can be accomplished
Dialogue via a third party	Many important uses (e.g., information room, data secretaries, telephone agents, counter clerks); enables management and the general public to obtain information from computers	Generally prevents extended use of the terminal

From James Martin, *Design of man-computer dialogues*. Copyright © 1973, pp. 10, 12-13, 34. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.

Key Terms

Dialogue design, mnemonics; person-computer dialogue

General Description

Before selecting a dialogue type for a particular application, the characteristics and abilities of the user must be accurately defined. Table 1 provides a comparison of eighteen approaches to interactive dialogue. For each dialogue type, advantages and disadvantages are noted; issues including limitations/advantages, user-type effects, cost considerations, and limitations of application are considered. Table 2 lists training and system response-time requirements for the major dialogue types.

Constraints

- Selection of the dialogue type should include consideration of user characteristics and abilities, hardware characteristics and limitations, information bandwidth requirements; and current state-of-the-art technology.

Key References

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Cross References

11.301 Steps in dialogue design;

11.313 System response time and the effect on user performance and satisfaction;

11.314 Information bandwidth in person-computer dialogue

Table 2. Training and response time requirements for selected dialogue types. (From Ref. 2)

Dialogue Type	Required User Training	Required System Response Time
Question and Answer	Little/none	Moderate
Form Filling	Moderate/little	Slow
Menu Selection	Little/none	Very fast
Function Keys with Command Language	High/moderate	Fast
User-Initiated Command Language	High	Fast
Query Languages	High/moderate	Moderate
Natural-Language	Moderate (potentially little)	Fast
Interactive Graphics	High	Very fast

11.304 Major Data Models in Database Systems

Key Terms

Computer system models; data displays; hierarchical models; natural language systems; network models; person-computer dialogue; query languages; relational models; user types

General Description

Database systems are composed of three interactive components: users, centralized data, and centralized interface. Centralization reduces data duplication, facilitates enforcement of data integrity and security controls, and creates an independence of data. The diversity of potential users makes it vital to tailor the interface to the appropriate user group. Implicit data models will be particularly difficult for users that have organizations of data different from that used by the database system. This problem can be somewhat alleviated by an appropriately designed interface. Models should include human factors considerations such as optimization of natural-language dialogues, screen layouts, and number of menu items.

The relational model (Ref. 3) uses a tabular structure (a "relation") in which the columns contain values from a single domain. Hierarchical models organize data elements into a tree structure. Network models (Ref. 1) group data elements into records, which are organized into data-structure sets via use of pointers. Other types of data models have been suggested, but these have not yet been implemented in commercial systems.

Constraints

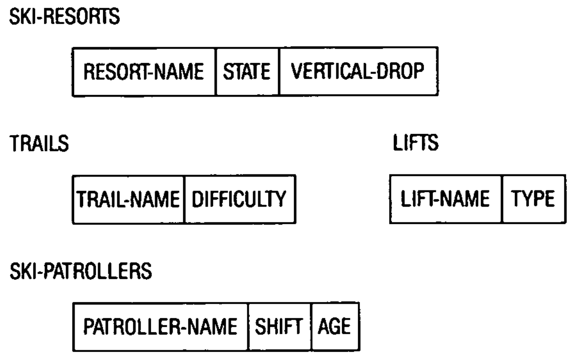
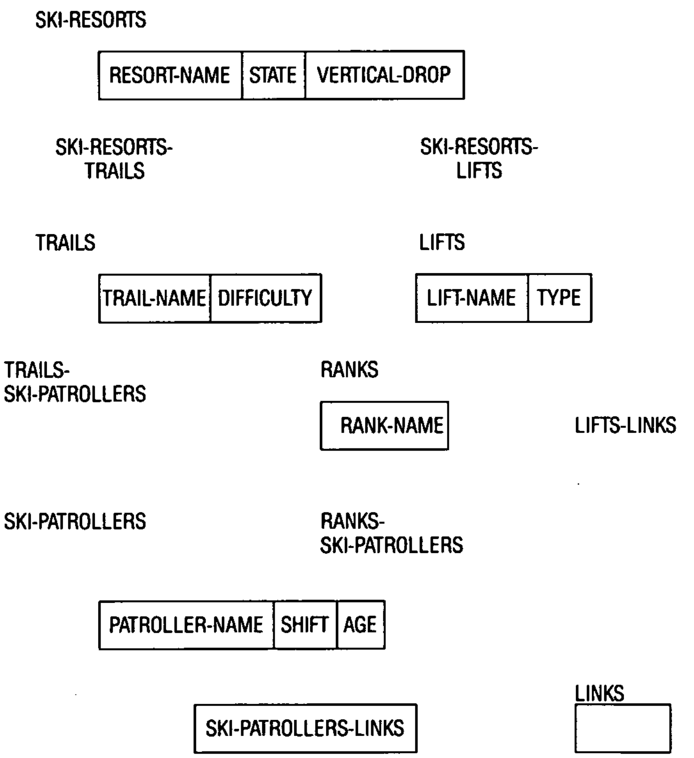
Selection of a data model requires consideration of:
- Type of user
- Logical organization of data
- Perception of data organization by potential users (Ref. 5)
- Human factors criteria, including simplicity, elegance, picturability, modeling directness, overlap with co-resident models, partionability of data, and nonconflicting terminology (Ref. 7)
- Selection of variable names to ensure comprehension by users

User confusion can result from:
- Restricted and formal meaning of common English words
- Misinterpretations of application-domain limitations when unrestricted natural language is used
- High number of relations in relational data models; fewer relations with more columns can reduce query complexity
- Inadequate "depth versus breadth" trade-offs in hierarchical data models
- Use of records with multiple-owner record types and cyclic schema in network data models

Table 1. Interface component of data base systems. (From Ref. 9)

Data Model	Characteristics	Query Language Type
A. Implicit Data Models	Does not provide logical view of data to user Involves knowledge of application area rather than data components	Natural Language Simple English Pseudo English English-like Computer Initiated Menu selection Question & answer Parameter specification
B. Explicit Date Models • Relational Example schema diagram for relational database: SKI-RESORTS || RESORT-NAME | STATE | VERTICAL-DROP TRAILS || RESORT-NAME | TRAIL-NAME | DIFFICULTY SKI-PATROLLERS || RESORT-NAME | TRAIL-NAME | PATROLLER-NAME | SHIFT | AGE LIFTS || RESORT-NAME | LIFT-NAME | TYPE	Avoids implementation details Promotes data independence Separates logical and physical data issues	Non-procedural languages

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Data Model	Characteristics	Query Language Type
• Hierarchical Example schema diagram for hierarchical information database: 	Easy to understand Limits complexity of data relationships Allows "one-to-many" relationships	Procedural, formal languages
• Network Example schema diagram for network-model database with LINKS and RANKS information: 	Includes additional features for: Organizing information Searching efficiency Storing records Controlling privacy Checking integrity Facilitating data administration Allows "many-to-many" relationships	Host-embedded data manipulation languages, including: PL/1 Cobol Fortran Assembler

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Cross References

11.301 Steps in dialogue design;

11.302 Basic properties of person-computer dialogue

11.305 Techniques for Modeling Interactive Systems

Table 1. Overview of interactive system modeling techniques. (From Ref. 7)

Approach	Characteristics	Source
A. Network models	Usually used to predict either the probability of failure or success, or the completion time, for an aggregate set of tasks Allow performance data about user and computer system to be integrated in a single model, even though original data came from a variety of sources	Refs. 1, 6, 9
B. Control-Theory Models	Usually used to predict overall performance of the user-computer system in continuous control and monitoring tasks More quantitative than other performance models, but ordinarily do not deal with details of the interface (e.g., display design)	Ref. 6
C. Decision-Theory Models	Can be used to suggest "optimal" decisions or to describe the observed decision-making behavior of users Frequently used in decision aids	Ref. 6
D. Models of Human Information Processing	Ideally lead to an integrative model of human information processing usable in a variety of design applications Existing models may be applicable to very specific tasks, if recognized as relevant	Refs. 5, 6, 10
E. Computer System Models	Can be useful in determining if user requirements with respect to response time and other gross system performance measures can be satisfied by a proposed system Usually attempt to predict such performance factors as system response time, central processing unit and memory loads, and input/output requirements	Refs. 2, 3, 4, 8

Key Terms

Control theory; decision theory; interactive systems; network models; person-computer dialogue; simulation; system modeling

General Description

Five approaches to modeling interactive systems are discussed in Table 1: (A) network models intended to define the relationships between system and user tasks in terms of expected performance and logical predecessor-successor relationships; (B) models based on control-theory, statistical estimation, and decision theory that regard users as feedback loop elements; (C) decision-theory models that allow selection of courses of action based on users' decision-making behaviors; (D) models of human information processing that analyze the problems to be solved and protocols used by problem-solvers during solution; and (E) computer-system models that describe only the computer component behavior of interactive systems and do not model the behavior of users in detail.

Applications

Examination of the effects of alternative designs prior to selection of appropriate dialogue design; evaluation of user and task properties.

Network Models

Linear tasks—single or multiple path

Control-Theory Models

1. Control-type tasks
2. Tasks with use of well-learned algorithms/procedures

Decision-Theory Models

Tasks with selection alternatives and evaluating outcomes

Models of Human Information Processing

1. Tasks with human as information processor
2. Models exist for well specified tasks when complete model is not necessary

Computer System Models

1. Descriptions of computer behavior
2. Determining if user requirements are satisfied
3. Optimizing overall performance in existing systems

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

Development of interactive system models, in general, is limited by several factors:

- Models based on memory and process limitations are restricted to simple tasks due to high detail demands.
- Validation of models used as dialogue design tools may not be practical.
- Successful models have been limited to simple task domains.
- Designer must thoroughly understand the task domain and information requirements.
- No general approach to model development is available.
- Other types of user-alone models exist but are not yet adapted to interactive systems.

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Cross References

8.124 Sentence comprehension: effect of syntactic structure;

8.128 Schema theory of memory for text;

11.301 Steps in dialogue design;

11.306 Keystroke model for predicting task execution time;

11.307 Protocol analysis for documenting user problems with interactive systems;

11.308 Formal language as a design tool for person-computer dialogue;

11.309 Playback methodology for evaluating person-computer dialogue;

11.310 Interface design principles derived from human error analyses

11.306 Keystroke Model for Predicting Task Execution Time

Table 1. Descriptions of the operators in the keystroke model.

Operator	Description	Time (sec)
K	Press key or button (includes shift or control keys). Time varies with skill:	
	Best typist (135 wpm)	0.08
	Average typist (55 wpm)	0.20
	Typing complex codes	0.75
	Worst typist	1.20
P	Point with mouse to target on display (follows Fitts' Law, range 0.8-1.5 sec)	1.0
H	Home—hands-on keyboard (or other device)	0.40
$D(n_d, l_d)$	Draw n_d straight-line segments of total length l_d cm (assumes drawing straight lines with a mouse)	$0.9n_d + 0.6l_d$
M	Mentally prepare (see Table 2 for application rules)	1.35
R(*t*)	Response by the system (only if it causes the user to wait)	*t*

Key Terms

Interactive systems; keyboard input; keystroke model; response time; task execution time; text editing

General Description

The keystroke model estimates the time required for an expert user to accomplish a given task using an interactive computer system. Task execution time is described in terms of four physical-motor operators (K, P, H, and D), one mental operator (M), and one system response operator (R), which are described in Table 1. Rules for placing the M operations are defined in Table 2. An encoding method is given for specifying the series of operators in a task prior to applying the equation:

$$T_{execute} = T_K + T_P + T_H + T_D + T_M + T_R$$

The keystroke model had been validated against eleven systems, with the calculated and observed times for task execution shown in Fig. 1.

Applications

Has been used to predict execution times in (1) text-editing, (2) computer-graphics tasks, and (3) system-executive tasks. Can be applied directly to tasks that are accomplished at a computer terminal using a keyboard and/or a mouse.

Method of Application

Given a task (involving a sequence of subtasks, the command language of a system, the motor skill parameters of the user, the response time parameters of the system, and the method used for the task), the keystroke model will predict the time an expert user will take to execute the task (not including errors). An example application is a text-editing task of replacing a five-letter word with another five-letter word, one line below the previous modification. Table 3 shows the task breakdown for two systems.

Using the operator times from Fig. 1 and assuming an average typing speed (t_K = 0.2 sec):

System A: $T_{execute} = 2t_M + 8t_K + 2t_H + t_P = 6.2$ sec

System B: $T_{execute} = 4t_M + 15t_K = 8.4$ sec

Table 2. Rules for placing the M operations. (From Ref. 2)

	All physical operations and response operations must be encoded. Use Rule 0 to place candidate M's, then cycle through Rules 1 to 4 for each M to see whether it should be deleted
Rule 0	Insert M's in front of all K's that are not part of argument strings proper (e.g., text or numbers). Place M's in front of all P's that select commands (not arguments)
Rule 1	If an operator following an M is fully anticipated in an operator just previous to M, then delete the M (e.g., PMK → PK)
Rule 2	If a string of MK's belongs to a cognitive unit (e. g., the name of a command), then delete all M's but the first
Rule 3	If a K is a redundant terminator (e.g., the terminator of a command immediately following the terminator of its argument), then delete the M in front of it
Rule 4	If a K terminates a constant string (e.g., a command name), then delete the M in front of it; but if the K terminates a variable string (e.g., an argument string), then keep the M in front of it

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Empirical Validation

The keystroke model was evaluated by comparing calculated and observed execution times in ten systems using 14 tasks, 28 operators, 1280 user-system-task interactions. The systems included three text editors, three graphics systems, and four executive subsystems.

The data from the validation studies are shown in Fig. 1, which compares the predicted and observed task execution times. The root-mean-square error was 21%.

Constraints

- The model applies to the behavior of experienced users, who have lower variability. No metrics are available for low or moderately experienced operators.
- The model assumes error-free performance.
- Proper task analysis and encoding are prerequisites.
- Tasks that require acquisition time (to perceive, read, or interpret displayed information) are not covered directly by the keystroke model.
- With highly repetitive tasks, users reduce their mental time below the model's predictions (M).
- The model does not apply to tasks that emphasize mental operations (e.g., composing text).

Key References

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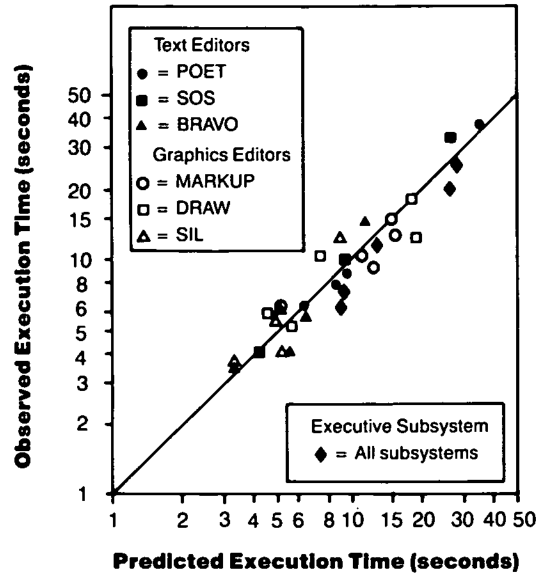

Figure 1. Observed execution times versus times predicted by the keystroke model. (From Ref. 2)

Cross References

11.307 Protocol analysis for documenting user problems with interactive systems;

11.308 Formal language as a design tool for person-computer dialogue;

12.401 Pushbuttons: effects of spacing, diameter, and orientation on error rate;

12.412 Control type, location, and turbulence: effect on data entry performance

Table 3. Breakdown of text-editing task for two computer systems.

System A		System B	
Jump to next line	MK[LINEFEED]	Reach for mouse	H[mouse]
Issue "Substitute" command	MK[S]	Point to word	P[word]
Type new 5-letter word	5K[word]	Select word	K[YELLOW]
Terminate new word	MK[RETURN]	Home on keyboard	H[keyboard]
Type old 5-letter word	5K[word]	Issue replace command	MK[R]
Terminate old word	MK[RETURN]	Type new 5-letter word	5K[word]
Terminate command	K[RETURN]	Terminate type-in	MK[ESC]

11.307 Protocol Analysis for Documenting User Problems with Interactive Systems

Table 1. Sample protocol analysis. (From Ref. 3)

Example:

Person-Machine Interaction	*Protocol Recording*
Section 1.3.1 S: Now, I can't remember the format of average, # it's A V G E or something. I'll try it out anyway. Sounds logical. No, I don't think we should have an E, we'll just try A V G. And we'll say PEOPLE and it'll probably fail.	#Language: Lexical (D N+
#10:20:53: ?: *T< – <:AVE:AGE;>PEOPLE State: Waiting with OUTPUT flag	#Language: Syntax (E N+ M+ <Syntax appropriate for <operators rather than <functions
Section 1.3.2 S: What has happened, output, # it worked, my goodness. Hang on, what has happened? Now I've got a message up here. (ENTER pressed here.)	#Language: interpretation (D N – <Interpreted OUTPUT as implying <correct solution
10:20:55 <AVG:AGE;> – ILLEGAL MONADIC OPERATOR 10:21:00: MESSAGE ID I18 State: Prompt with blank field	
Section 1.3.3 S: Illegal monadic operator. # I don't know whether that's a mistake for nomadic or not...	#Language: Interpretation (D N+

Key to System and Task Characteristics (Specific to system under analysis; may require modification as application changes.)

— *The workplace environment:* comfort, lighting and noise.
— *The terminal keyboard:* keying errors, confusions and delays.
— *The terminal display:* legibility and formatting.
— *General system operating characteristics:* control of the terminal, system response time, allocation of space.
— *The interactive language:* lexical, syntactic and semantic
— *The interactive language:* interpretation of system responses.
— *Task organization influenced by the system:* imposed goal structures.
— *Task organization independent of the system:* conditions of the study.

Key to Symbols Used in Protocol Observations
= event categorizations
(E = errors
(D = difficulties
(R = reminiscences
M+ =created system error message
M– =no system message generated
N+ =noted by user before or when occurred
N– =unnoted by user
< = explanatory comments
State =definition of system state after a user input

Key Terms

Block interaction model; cognitive mismatch; goal structure model; information processing model; interactive systems; person-computer dialogue; protocol analysis; state transition model; system documentation; verbal protocols

General Description

Protocol analysis provides identification and documentation of cognitive mismatch between human and computer in interactive systems. This methodology involves a formalized interactive session during which terminal protocols (user performance) and verbal protocols (user-expressed cognitive activity) are observed and recorded. For verbal protocols, the system user must be required to describe the aim and the expected system response before entering each command. Use of documentation or taking of notes by the system user is not allowed. Both protocols provide complementary information: terminal protocols describe directly observable user behaviors and verbal protocols describe concurrent thought/reasoning processes or cognitive activities of the user. Collectively, the two protocols provide data from which hypotheses of user-computer mismatch can be formulated for empirical resolution.

The experimenter must merge the two protocol streams into a single recording of the session, since the two are either concurrent or sequentially occurring. Distinctions, however, are maintained between problems in terminal protocol and verbal protocol. Problems deduced from terminal protocol are referred to as *errors*, those deduced from verbal protocol (or from both sources) are *difficulties*, and those from recollections of previous difficulties or errors are *reminiscences*. Each of these classifications is used to categorize interactive *events*. An example protocol session is provided in Table 1, including the keys for the protocol recording. To facilitate ease of collection and categorization, protocol observation data are coded in accordance with a standardized criterion.

The chronicled events can also provide input for generation of hypotheses by models. One model, the *block interaction model*, analyzes the separable classes of knowledge in the user's head that are drawn upon during the interaction. Classes of knowledge include the user's representation of the problem, knowledge of the system, general knowledge of other systems, natural language, and so on. Note that this differs from the categorization scheme that deals only with system knowledge. The block interaction model defines the possible forms of interference between the classes of knowledge.

A goal structure model allows representation of the planning behind a sequence of dialogue and predicts the occurrence of certain classes of error at certain stages in the dialogue. Likewise, the user's internal representation of the state of the machine and how it changes with user actions can be contrasted with the true state of the machine by means of representation derived from a *state transition model*. The identification of system states particularly prone to error has consequences for the type of feedback that the system should present to the user (e.g., which states should be defined by display flags).

The *information processing model* calls upon current models in cognitive psychology dealing with relevant processes, such as language analysis and production, information storage and retrieval, and keyboard skills. A prediction of information storage models is that an item that is confusable with other items or that cannot easily be discriminated from them will be difficult to use and remember. Multiple use of the same character for different purposes is an example of a potential source of confusion that could be used to explore the model.

Applications

Documentation of person-computer interface mismatch; hypothesis generation for empirical research; validation of models.

Method of Application

Example of System Evaluation: The most common cause of error was mistyping (33% of all errors). Further analysis showed that, with the majority of errors (51%), the correct key was pressed but in the wrong shift. Subjects identified this as a problem: "I definitely think the worst thing about this is the number of times you have to use the shift key." This issue could have been discovered at the design stage had an evaluative study been performed. The probable remedy would involve changing the character set.

Constraints

- System user must be capable of, and willing to, verbalize the reasoning associated with system usage.
- Requires interpretation by the researcher of system users' verbal reports.
- User reports may be incomplete; information that is obvious to the user may not be verbalized.
- Possibility exists that problem-solving may be affected by concurrent verbalizations (Ref. 5).
- Tasks to be performed by system users will be determined by the purpose of the study.
- Observational studies on an existing system should not be used as substitutes for considering human factors principles in the design.

Key References

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5. Newell, A., & Simon, H. A. (1972). *Human problem solving*. Englewood Cliffs, NJ: Prentice-Hall.

Cross References

11.306 Keystroke model for predicting task execution time;

11.308 Formal language as a design tool for person-computer dialogue;

11.309 Playback methodology for evaluating person-computer dialogue

11.308 Formal Language as a Design Tool for Person-Computer Dialogue

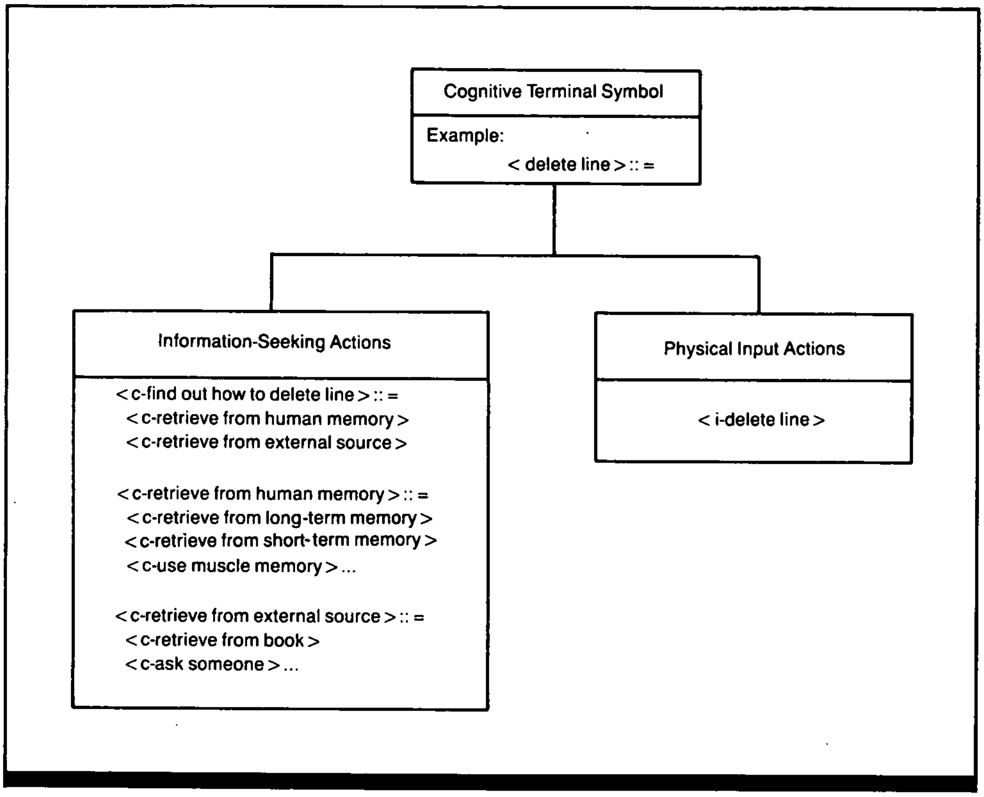

Figure 1. Elements of user-action language; c = cognitive action, i = input action

Key Terms

Guideline verification; interface design; person-computer dialogue; system documentation; user model

General Description

The use of formal grammar as an analytic predictive tool to aid person-machine interface design is enhanced by (1) defining the concepts involved, (2) making explicit the prediction process, and (3) reducing limitations of predictions. The incorporation of cognitive (mental) information into the grammar permits differential system description for various classes of users. The prediction process includes assumptions that allow incorporation of results from the psychological literature to expand the limits of prediction.

Figure 1 depicts the language used to describe user actions. Two kinds of actions are considered: information-seeking actions (both cognitive and physical) and physical input actions (observable inputs to the system). The examples shown label the two actions with the symbols "c" for cognitive or "i" for input.

An overview of the prediction process is presented in Table 1. Grammatical models (Step 1) do not deal with experimentally verifiable terms. Conversion is accomplished by Step 2, rewriting terminal symbols as sentences in a new grammar using units of time or error (e.g., "<move cursor>": $= t_{\text{move cursor}}$). Comparative predictions can then be made using these sentences. For example, to compare system use by different user classes, the possible retrieval sources (e.g., book, human memory) are presented as alternations in the cognitive rules in the grammar (Fig. 1). In deriving the sentences corresponding to each class of user (Step 3), appropriate information-seeking action is selected. Thus, a naive user might be expected to use an external source (e.g., book), while an experienced user could retrieve this information from memory.

To make the prediction process explicit and powerful, the assumptions on which the predictions are made must be explicit and quantifiable (Step 4). These assumptions are made from common sense and the experimental findings of human factors and psychology. Assumptions are written as inequalities or other equations, such as: time to retrieve information from an external source (e.g., book) will be greater than time to retrieve from human long-term memory, i.e., ($t_{\text{text}} > t_{\text{LTM}}$). On the other hand, for a particular sequence of keystrokes, and for users who type at the same typing speed, time to type the sequence will be the same.

Interrelationships between assumptions can also be made explicit. For example, if it is assumed that (1) time to find information in an external source is much greater than time to perform a typing action, and that (2) time to perform a typing action is greater than time to retrieve information from human memory, the order among the three quantities is obvious. Predictions are made (Step 5) by algebraically solving the quantified terminal statements and prediction assumptions.

Applications

Formal description of user interfaces; general analytic and predictive design aid.

Method of Application

As an example, suppose predictions are to be made about naive versus skilled users whose typing speeds are equivalent. Two sentences from the grammar would be derived, one for each of the user classes. The cognitive and the input actions would be converted to variables representing times. The input actions would be the same, but the information-seeking actions would differ. Naive users would rely on the external source (e.g., book); experienced users would rely on memory. The prediction assumptions would tell us that time to retrieve from an external source is greater than time to retrieve from human memory. Therefore, a prediction would be made that corresponds to our intuition: Naive users would take longer on this task.

Table 1. Elements of the prediction process.

1. An action grammar describing both cognitive and input actions
2. Extensions to the grammar to convert these actions to time or errors
3. Sentences derived from the grammar for particular tasks and classes of users
4. A set of prediction assumptions drawn from common sense, psychology, and/or human factors
5. Substitutions from the appropriate assumptions into the sentences to be compared, and solution according to the normal rules of simple algebra

Empirical Validation

The approach is currently being validated.

Constraints

• Some of the predictive assumptions, if not all, will appear too simple, but their importance to the model is paramount; explicitly stated assumptions allow analysis and resolution of crucial or controversial issues.

• Cognitive assumptions can be treated in a variety of ways to draw upon the literature, but broad familiarity with psychological literature is required.

Key References

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Cross References

11.306 Keystroke model for predicting task execution time;

11.307 Protocol analysis for documenting user problems with interactive systems

11.309 Playback Methodology for Evaluating Person-Computer Dialogue

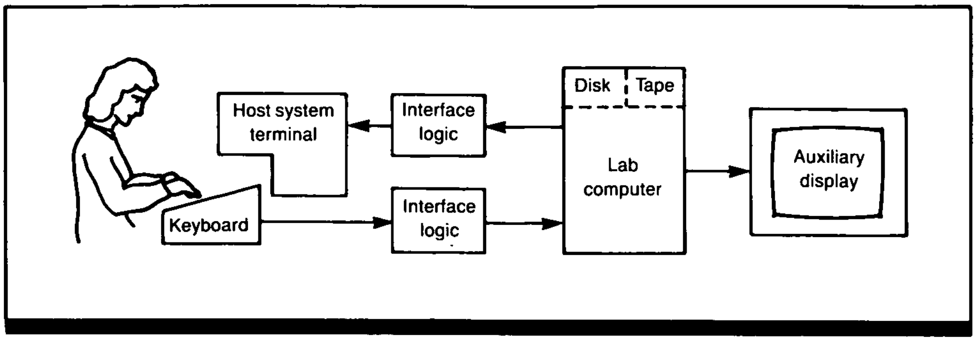

Figure 1. Schematic diagram of playback system. (From Ref. 2)

Key Terms

Dialogue design; person-computer dialogue; playback analysis; system evaluation

General Description

Playback is a general-purpose data-collection program to evaluate user performance with person-computer interfaces. Measurements of ease-of-learning may include:
1. Time to complete a training program
2. Time to achieve a performance criterion
3. Observed difficulty in learning a procedure
4. User comments, suggestions, and preferences

Measurements of ease-of-use after initial learning may include:
1. Time to perform selected tasks
2. Success in task completion
3. Frequency of use of commands or language features
4. Time spent locating information in documentation
5. User comments, suggestions, and preferences

Other measures of user problems could include:
1. Inability to find information in documentation
2. Frequency with which each error message is encountered
3. Frequency in using on-line help
4. Use of special assistance (simulated product support)

Apparatus

Playback provides a method for unobtrusively measuring these variables and storing the data for post-hoc analysis. Figure 1 diagrams the playback-system configuration. The interference logic box provides interception of keystroke-level user behavior for time-stamp and storage in the lab computer. Time is recorded to msec tolerances.

The experimenter station (Fig. 2) provides remote observation of user behaviors, on-line interaction with the software, and the use of documentation. The experimenter records objective observations (codes and narrative comments) to supplement the keystroke-level data in the playback analysis.

Analysis

Playback analysis can be performed at various points of the data collection, after all of the required user sessions or after selected sessions. The playback software permits analysis of user behaviors by "playing back" sequences of user keystrokes in any of four pacing units selectable by the experimenter:
1. Next character or function
2. All characters up to and including the next interrupt
3. All characters and functions up to and including the next interrupt
4. All characters up to and including the next function with the same time intervals as when originally keyed by the user

Pacing units can be changed at any point in the analysis and sequences of interest can be repeated at will. During the playback analysis, the experimenter can further annotate user behaviors, as during data collection. Figure 3 is a sample page of a playback analysis.

The playback software computes and records the following objective statistics for each session:
1. Time from session beginning until user's first keystroke
2. Time from session beginning until user's last keystroke
3. Cumulative use of each "Help" condition
4. Frequency of use of each function key
5. Number of requests for help
6. Frequency of use of selected commands

Applications

Dialogue simulation experiments; design of new person-computer dialogue; troubleshooting problem dialogue.

Constraints

- Validation of playback methodology has not been published in the literature reviewed.
- The amount of data obtained may be overwhelming.
- Playback provides analyses of terminal protocol and observed incompatibilities only; it does not provide systemized collection of verbal protocols, modeling of cognitive incompatibilities, generalization of models and hypotheses, or the following analysis of results:
  - —Workplace environment: comfort, lighting, noise
  - —The terminal keyboard: keying errors, confusions, and delays
  - —The terminal display: legibility and formatting
  - —General system-operating characteristics: control of the terminal, system response time, allocation of space
  - —The interactive language: lexical, syntactic, and semantic
  - —The interactive language: interpretation of system responses
  - —Task organization influenced by the system: Imposed goal structures
  - —Task organization independent of the system: conditions of the study

Key References

1. Hammond, N., Long, J., Clark, I., Barnard, P., & Morton, J. (1980). Documenting human-computer mismatch in interactive systems. In *Ninth International Symposium on Human Factors in Telecommunications.*

*2. Neal, A. S., & Simons, R. M. (1983). Playback: A method of evaluating the usability of software and its documentation. In A. Janda (Ed.), *Proceedings of CHI-83 Human Factors in Computing Systems* (pp. 78-82). New York: Association for Computing Machinery.

Cross References

11.301 Steps in dialogue design;

11.306 Keystroke model for predicting task execution time;

11.307 Protocol analysis for documenting user problems with interactive systems;

11.308 Formal language as a design tool for person-computer dialogue

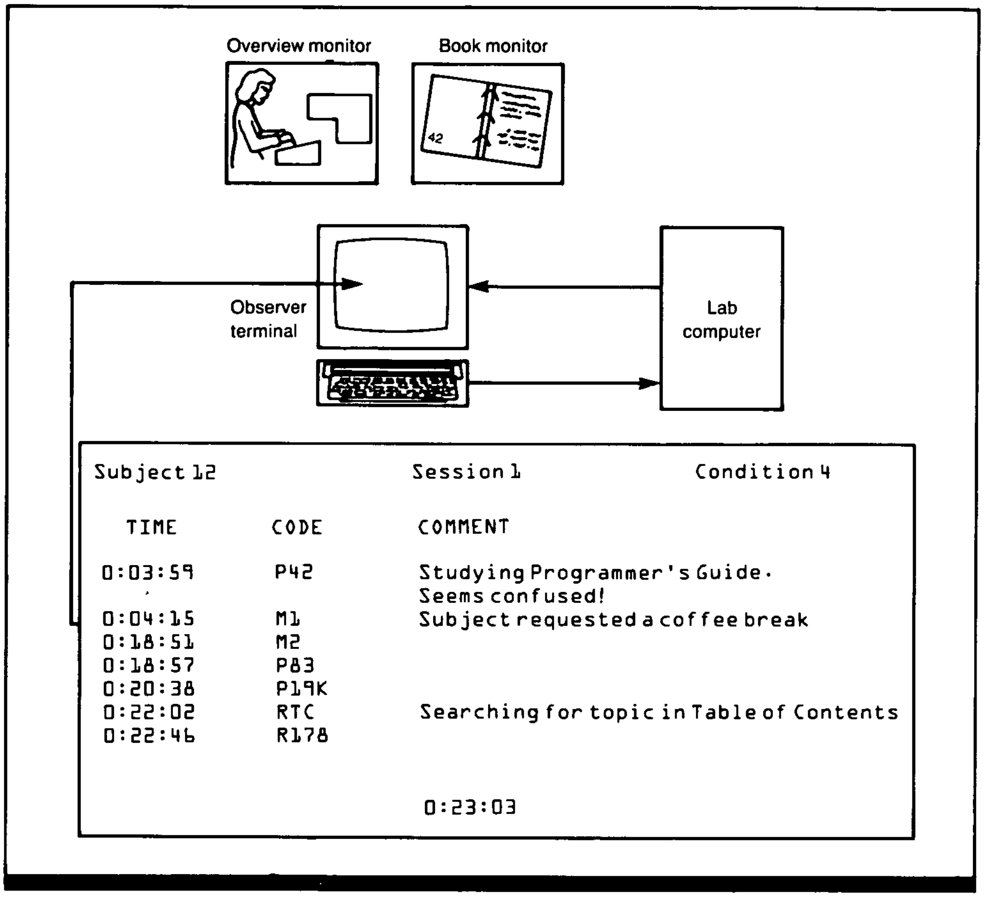

Figure 2. Experimenter station and sample of objective observations. (From Ref. 2)

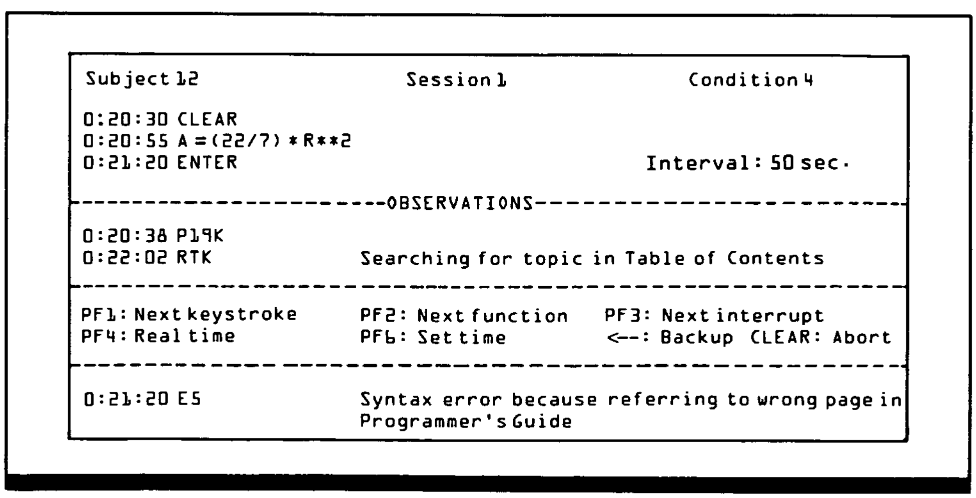

Figure 3. Example of a playback screen. (From Ref. 2)

11.310 Interface Design Principles Derived from Human Error Analyses

Key Terms

Activation errors; capture errors; cognitive engineering; description errors; human performance reliability; interface design; schemas

General Description

Analyses of the frequency, cause, and consequence of user errors provide information for designing more effective user-machine interfaces. Error analysis cannot address all classes of problems and should be supplemented with analyses of the user's information-processing capabilities and mental model of the system.

A general analysis of human errors, both in everyday events and in usage of computer systems, yielded the taxonomy of human errors given in Table 1. For selected error types, Table 2 presents the general cause of the error, an example, and preventive/corrective actions. The design rules follow the general principles of providing feedback to users, use of distinctive command sequences, protection against inadvertent activation of critical or fatal actions, and consistency.

Applications

Design of man-machine interfaces; design of person-computer dialogue; design and layout of controls; design and layout of displays.

Constraints

- These data form only the early stages of a "cognitive engineering" discipline; further research will provide additional design principles based on cognitive theory. Because these data summarize only analyses of human performance and errors, incorporation of analyses of human information-processing and users' mental models will also be needed for a well-rounded discipline.
- Use of these data depends upon highly detailed knowledge of the user populations, man-machine interface, and error analyses.
- This taxonomy of errors is only one of many available.

Table 1. Classification of errors. (From Ref. 3)

1. Slips in the formation of intention
   a. Mode errors: erroneous classification of the situation
   b. Description errors: ambiguous or incomplete specification of the intention
2. Slips resulting from faulty activation of **schemas**
   a. Unintentional activation: when schemas not part of a current action sequence became activated for extraneous reasons, and then are triggered and lead to slips
   b. Capture errors: when a sequence being performed is similar to another sequence that is used more frequently or is better learned, the latter sequence may capture control
   c. Data-drive activation: external events cause activation of schemas
   d. Associative activation: currently active schemas activate others with which they are associated
   e. Loss of activation: when schemas that have been activated lose activation, thereby losing effectiveness to control behavior
   f. Forgetting an intention (but continuing with the action sequence)
   g. Misordering the components of an action sequence (including skipping steps and repeating steps)
3. Slips resulting from faulty triggering of schemas
   a. False triggering: a properly activated schema is triggered at an inappropriate time
   b. Spoonerisms: reversal of event components
   c. Blends: combination of components from two competing schemas
   d. Thoughts leading to actions: triggering of schemas meant only to be thought, not to govern action
   e. Premature triggering
   f. Failure in triggering: when an active schema never gets invoked because:
      (1) Action was preempted by competing schemas;
      (2) There was insufficient activation, either as a result of forgetting or because the initial level was too low; and/or
      (3) There was a failure of the trigger condition to match, either because the triggering conditions were badly specified or the match between occurring conditions and the required conditions was never sufficiently close.

Key References

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5. Rigby, L. (1970). The nature of human error. *Annual Technical Conference Transactions of the ASQC*. Milwaukee, WI: American Society for Quality Control.

6. Singleton, W. T. (1977). Techniques for determining the causes of errors. *Applied Ergonomics, 3,* 126-131.

7. Swain, A., & Guttman, H. (1980). *Handbook of human reliability analysis with emphasis on nuclear power plant applications*. Albuquerque, NM: Sandia Laboratories.

Cross References

11.301 Steps in dialogue design;

11.320 Error recovery

Table 2. Reduction of selected error types. (From Ref. 3.)

Error Type	Cause	Example	Prevention/Correction
Mode errors	Lack of clear feedback as to current state	Computer text editor 1. issuing commands in text mode 2. entering text in command mode Pushing buttons on complex digital watches Entering data on autopilots of commercial aircraft	Provide more feedback and indication of current system state
Description errors	When different actions have similar descriptions, either in specification of the action or in the class of argument Control panels without adequate distinctions among controls for quick glance or peripheral vision inspection	Multiple-use keys in computer text editors (e.g., "d," "shift-d," "control-d") Throwing switches or operations of controls 1. altimeters 2. radio frequencies 3. transponder codes 4. nuclear power plant control rooms Derivation of unknown command structure by analogy with similar (known to user) command	Arrange instruments and controls in functional patterns Shape code controls for distinctiveness Make actions with critical implications difficult to perform Organize computer screens and menus functionally Design command language or menu headings to be distinct in appearance and required actions Consistency in command sequence formation
Capture errors	Overlap in sequence required for performance of two different actions when one is more familiar than the other. Familiar act takes precedence over unfamiliar act	Berkley release of UNIX operating system write-file option: :W = write file :Q = quit editor :WQ = write, then quit if :WQ is most frequently done and intention is to write and continue editing (:W), one may err and enter :WQ	Minimize overlap by using vastly different commands Determine critical points where errors occur and design system to flag or otherwise bring to operator's attention
Activation errors	Inappropriate actions are performed Appropriate actions are not performed	Inappropriate action—sequence activation resulting from relation to desired sequence Failure to perform action from memory failure	Provide memory aids Design system for tolerance of errors

11.311 Taxonomy of Computer-User Characteristics

Table 1. Taxonomy of interactive system users: selected dimensions. (From Ref. 2)

1. Knowledge or expertise as a computer programmer, systems analyst, computer operator, or other computer-related specialist
2. Knowledge concerning the specifics required for carrying out the job. What can be assumed concerning the user's understanding of how a particular application is to be carried out?
3. The extent to which user's job or activity will focus on interactive terminal usage. Will the terminal be used on a dedicated or casual basis? Will the terminal serve as an information source or as the basis for regular work performance?
4. Level of decision-making authority and responsibility
5. Educational background
6. Availability of special skills or aptitudes such as clerical skills, managerial skills, mathematical skills
7. Expected duration of stay in particular job; employee turnover
8. Sources of job-related motivation. Is the use intrinsically motivated or must the interactive tasks be designed to promote motivation?
9. Extent to which terminal usage will be an option versus a job requirement
10. Attitudes toward computer technology and its introduction into the work setting

Key Terms

Computer-user characteristics; front-end analysis; interactive systems

General Description

A frequently emphasized facet of interactive-system design is knowledge of the user population. Precise description of the important variables, however, is left open to interpretation. The resulting actions are not often in accordance with what will be truly useful (Ref. 1). "Know thy user" must go beyond mere identification and stereotyping of the user population, especially when these data are obtained through indirect means or logical conjecture. Without direct contact between the designer and user groups, underestimation of the diversity and capabilities of the user groups can occur. Interaction between designers and users can provide valuable insights into the differences between designers of systems and users of systems.

Table 1 lists ten dimensions of users that should be considered by system designers. Although the characteristics cannot be linked directly to specific design guidelines, these data provide background information for design of systems that are user compatible.

Applications

Front-end analysis of user characteristics; selection of dialogue type.

Constraints

- Application of these data is limited by the depth/breadth and validity of the data collection.
- Variability of user populations on these dimensions may be extremely high in some application areas.
- Few user characteristics have been validated as reliable predictors of performance with computers.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Gould, J. D., & Lewis, C. (1983). Designing for usability—Key principles and what designers think. In A. Janda, (Ed.) *Proceedings of CHI '83 Human Factors in Computing Systems* (pp. 50-53). New York, : Association for Computing Machinery.

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Cross References

11.301 Steps in dialogue design;

11.303 Comparison of approaches to person-computer dialogue

11.312 Designing for the Casual or Infrequent Computer User

Key Terms

Database query systems; natural language systems; query languages; training

General Description

Design of data retrieval systems and dialogue for casual, novice, or infrequent users differs greatly from the design of systems specifically intended for experienced or professional users. Designers must consider the consequences of infrequent use, including poor retention of system and training details. Productive design efforts will emphasize principles, rather than details, for effective user training. Error detection and correction functions can be guided by the system to combat the typical error-prone nature of an infrequent user's query. Casual users expect (and need, if maximum efficiency is to be attained) a system that feels natural, i.e., corresponds with their "noncomputer" dialogue perceptions. These include courteous, rational, and informative interactive dialogue that can also deal with the foibles of human dialogue, such as tolerance for imprecise logic or specifications, implicit or contextual references to previous queries, and requests for additional information. Failure to specifically consider the abilities and needs of the casual user can result in poor user performance due to extended time in training, increased error frequency and error recovery time, high amounts of inadvertently retrieved data, and/or extensive amounts of time negotiating the dialogue. Other results of inadequate dialogue design for the casual user can be reluctance or refusal to use the system. Table 1 presents selected guidelines for design of systems where there are casual users.

Applications

Query language development; database systems; management information systems.

Constraints

- Requirements of casual users have not been subjected to extensive study.
- Most of the guidelines are not based on experimental studies; others are based loosely on empirical findings.
- Design must include numerous trade-offs if multiple user groups are anticipated and multiple dialogue types are not feasible.

Key References

1. Cuff, R. (1980). On casual users. *International Journal of Man-Machine Studies, 12,* 163-187.

Cross References

11.301 Steps in dialogue design

Table 1. Selected guidelines for designing person-computer dialogue for the casual user.

Design for a Forgetful User

1. Train users in principles, not details
   a. Emphasize conceptualization of systems as a whole
   b. Provide concise groundings in the principles of the interface
   c. Do not rely on existing skills in users
2. Provide explicit, constrained choices for user inputs
   a. Use menu selection or prompting messages
   b. Make available choices apparent
3. Use natural language interface for communication on user's terms, and provide system guidance
   a. Restrict queries within system competence
   b. Continue progression of a dialogue
   c. Supplement information presented in display, preferably on-line

Minimize System-Provided Opportunity for User Errors

1. Limit number of things user must consider at one time
   a. Menu selection: 10 or fewer items; consistent selection method
   b. Prompting systems: restrict responses to well-defined range of values; utilize query-in-depth for system-initiated remediation of inappropriate responses
2. Include corrective features in system-detected errors
   a. Attempt prediction of user's intended entry
   b. Initiate sub-dialogues for clarification
   c. Describe corrective actions in error messages
3. Word error message for user acceptance
   a. Use humble wording to retain user's goodwill
   b. Provide at least two alternatively phrased messages

Provide Feedback for User Guidance and Reassurance

1. Include unambiguous system responses for all user entries
   a. Reinforcement of correct responses
   b. Error detection
   c. User identification of system actions
2. Use easily understandable dialogue
   a. Avoid computer jargon
   b. Avoid unusual terms or abbreviations
3. Maintain a natural flow of dialogue
   Natural ordering of questions and inputs

Match Database Query System to Infrequent User's Abilities

1. Reduce data-structure, content, or semantic-knowledge requirements
   a. Data should be requested by descriptive terms
   b. System should guide user through valid choices
   c. Requests by field (attribute) or record (relational) names should be minimal
   d. Names and descriptive phrases should be displayable upon user request
   e. When multiple logic paths occur, choices should be explained in user-oriented terms
2. Design for deviations in query precision
   a. Anticipate vague, exploratory queries before precise questions
   b. Guard against excessive output from broad or erroneous requests, even if query appears legitimate
   c. If specific attributes of an entity are requested, consider supplying others to facilitate query formulation and data retrieval
3. Match dialogue language to the needs and abilities of users
   a. Reduced language formality can facilitate casual users
   b. System-aided syntax-error detection/correction is desirable
   c. Implicit logic specification is less error-prone than explicit use of logical connectives and quantifiers
   d. Plan for logical errors in syntactically correct queries if explicit logic is required

11.313 System-Response Time and the Effect on User Performance and Satisfaction

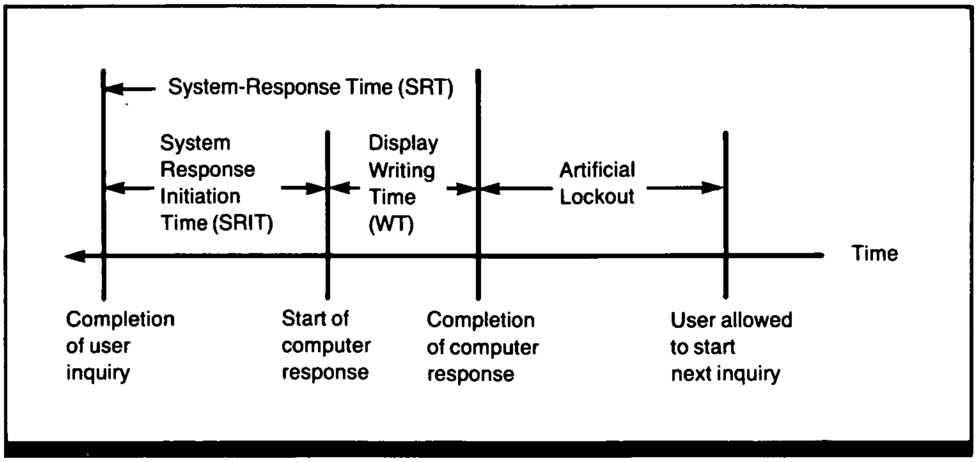

Figure 1. System-response time definitions. (From Ref. 10)

Key Terms

Artificial lockout; conversational dialogue; light pens; person-computer dialogue; system-response time

General Description

System-response time (SRT) is the time delay between the completion of a user inquiry and the completion of the associated computer response (e.g., completion of display writing; Fig. 1) (Ref. 10). Degradation in user performance is a nonlinear function of SRT when certain time criteria are violated. Four major SRT categories have been identified (Refs. 2, 12, 13):

1. SRT >15 sec:
   a. Too slow for conversational dialogue
   b. Message of expected delay is desirable
   c. Desirable to free user from captivity of waiting for system
   d. Allow user to get answer at own convenience
2. SRT = 5-15 sec:
   a. Too slow for interactive conversation
   b. Frustrates users in problem-solving and data-entry activities
   c. Allows unproductive behavior or shifts to other task
3. SRT = 2 sec: Too slow for users at high concentration level
4. SRT is almost instantaneous

Variation in SRT can be as detrimental as long SRTs (Ref. 10). General recommendations are:

SRT	*Maximum Variability*
0-2 sec	± 5%
5 sec	± 10%
>5 sec	± 15%

Acceptable SRTs are dependent upon a user's expectations of system performance and perceived system activities. Table 1 lists recommended SRTs and maximum variability for specific user activities/tasks. Reduction of SRT below the user's preparation time provides little or no performance advantage (Refs. 4, 9).

Table 1. Recommended system response times. (Adapted from Ref. 5)

User Activity/Task	Activity/Task Explanation	Maximum Response Time (95 Percentile Occurrence)	Recommended Time	Time Variability Allowed for No User-Perceived Difference in Response Time
System activation	User initiating a session with a terminal or other device	3 sec	1 sec	±10%
Request for service	System availability and responsiveness to a user depends on type and difficulty of work to be performed			

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

User Activity/Task	Activity/Task Explanation	Maximum Response Time (95th Percentile Occurrence)	Recommended Time	Time Variability Allowed for No User-Perceived Difference in Response Time
Simple service	Routine single step operation; Example: request for menu display page	2 sec	0.5 sec	±10%
Complex service	A multiple section or step task where a number of operations must be performed; Example: send message (transmission/ line communication), process data, return message (transmission line communication), etc.	5 sec.		
Loading and restart	Program and data loading called for by the user	15-60 sec	<30 sec	±15%
Information on next procedure—interactive conversational mode	Conversational interaction with a terminal requesting next step or procedure in a computer-aided or guided task	<5 sec		±10%
Information on next procedure—one part of a multi-part job	Factory worker, etc. requesting next job assignment (non-dedicated terminal operation)	10-15 sec		±15%
Response to simple inquiry from list	Query addresses existing record or record-string that can be directly retrieved and displayed; example: Give physical description of part #12345678	2 sec		±10%
Response to simple status inquiry	Asks for one category of information about an unambiguously identified object; if system may have to do some searching and processing to assemble response, delay may be extended to 7-10 sec. User must be informed of delay at start of processing delay.	2 sec (7-10 sec)		±10%
Response to complex inquiry in table form	Requires collecting and displaying data on the basis of logical relations among categories. It assumes an "image" of the displayed response does not pre-exist in the system.	2-4 sec (7-10 sec)		±10%
Response to request for next page	When text or data is continued from page to page, the time delay for the first few lines on the new page should be <1 sec.	0.5-1 sec	0.5 sec	±5%
Response to execute problem	Longer response delays will initiate user to move to secondary tasks not directly related to the terminal	<15 sec	<15 sec	
Response to user intervention in automatic process	System response to user that the user command has been received and will be executed	4 sec		±10%

(Continued)

Table 1. (*Continued*)

User Activity/Task	Activity/Task Explanation	Maximum Response Time (95th Percentile Occurrence)	Recommended Time	Time Variability Allowed for No User-Perceived Difference in Response Time
Error feedback (following completion of input)	User input errors detected by the system or application brought to the user's attention; response time does not apply to hardware-related or processing errors	0.5-2 sec	1 sec	±10%
Response to control activation	Hardware-related detection and operation response to user activities; example: a signal that key depression, credit card read, or forms insertion has physically activated the device			
Key activation (alpha/numeric and control keyboards)	Response or feedback of physical key operation (such as key-bottoming sound) should be immediate, because high-speed operation of keys may occur 10 msec apart in bursts		<10 msec	
Hardware response to credit card operation or forms insertion operation	Response or feedback indicating only that a card or form has physically activated the hardware. Response may be auditory click, or visual or tactile signal that user activity has been noticed by the machine	0.4-0.5 sec	0.1 sec	Should be fixed
System acceptance response to control activation	System response to a user activity, which means that a processor, etc. has been informed of the user activity and is responding with a signal of acceptance, rejection, proceed to next task, etc.			
Key activation acceptance (alpha/numeric and control keyboards)	Feedback of key operation being accepted by the system (buffer, processor, etc.) should be immediate because high-speed operation of keys may occur 10 msec apart of bursts	May vary with application	<30 msec	
Response to credit card operation or forms	Response or feedback indicating proper or improper card or forms by the system. Also could indicate that this action has been completed and machine is ready for next user activity	2-4 sec	1 sec	Should be fixed
Response to light pen requests	Request for image or format by touching light pen to code name, code number, or display position	1 sec	0.5 sec	±5%
Drawings with light pen (used as stylus)	Drawing lines on display face where direction and shape of line have significance and movements are relatively slow	0.1 sec		±5%
Light pen control activation	Response to user activation of pen switch indicating that switch has operated	0.1 sec	0.1 sec	±5%

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Interactive computer systems in which conversational dialogue, rather than on-line batch dialogue, is the intended mode. Situations where human performance and satisfaction are paramount to a system's successful mission or use.

Constraints

- Artificial layout (Fig. 1) may improve complex problem-solving performance but reduce user satisfaction (Refs. 1, 6, 12).
- Effects due to display writing time (Fig. 1) have not been adequately researched.

Key References

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Cross References

11.301 Steps in dialogue design;

11.336 Guidelines for the use of noncritical auditory signals

11.314 Information Bandwidth in Person-Computer Dialogue

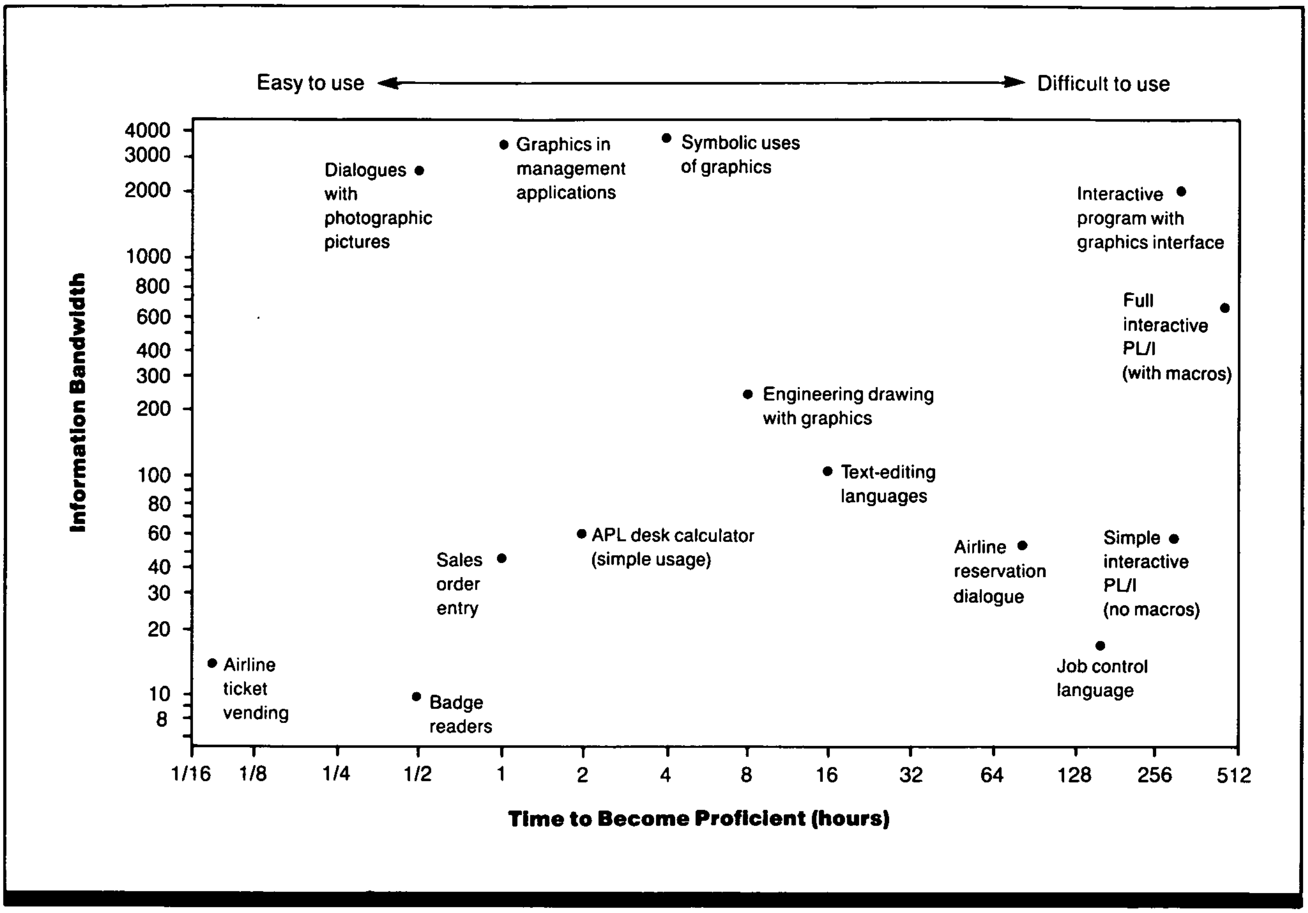

Figure 1. Dialogue power and ease-of-use. (From James Martin, *Design of man-computer dialogues*, © 1973, pp. 10, 12-13, 34. Reprinted by permission of Prentice-Hall, Inc., Englewood Cliffs, NJ.)

Key Terms

Dialogue design; information bandwidth; information coding; information portrayal; multiple purpose dialogue; person-computer dialogue

General Description

Information bandwidth is the quantity of information communicated or decisions made in a given time using a dialogue. In designing dialogues for general use, a trade-off must be made between ease of use and information bandwidth based on the characteristics of the user. Information bandwidth is highly dependent on the efficiency of information coding. Although some user types (professionals and managers) may require a high bandwidth of information, system acceptability may be low if the system is difficult to use. Highly desirable dialogues (large quantity of information and easy to use) appear in the upper left quadrant of Fig. 1. The lower right quadrant includes dialogues to be avoided due to narrow application and dependence on highly proficient users.

The rate of change for variable data displays in the screen design must be limited to maintain consistency with human information-processing limitations. Suggested limitations include no more than a 1-Hz update of the most important dynamic information, and a limit of the proportion of dynamic data being displayed to 40% of the displayed parametric data (Ref. 1).

For displays with higher information bandwidths, it is imperative to consider related variables such as coding, formatting, and structuring of the data display.

Applications

Selection of dialogue mode based on characteristics of the users' abilities/needs; multiple-application (general purpose) dialogue design.

Constraints

- Information bandwidth is not necessarily proportional to physical-channel bandwidth.
- For development of the figure, information bandwidth was subjective (estimate of number of basic assembler-code lines equivalent to 5 min of dialogue).
- Efficiency of the dialogue does not predict the usefulness of dialogue.
- *Major* differences exist between easy-difficult and high-low information bandwidth dialogues.
- High flexibility or power (potentially desirable characteristics) may result in greater user training time to become proficient.
- "Undesirable" dialogues may hold utilitarian value for specific or narrow applications.
- Easy-to-use/high information bandwidth dialogues can substantially increase the hardware, communications, and programming complexity.

Key References

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Cross References

8.101 Perceiving visual language;

8.106 Visual language processing of words and pictures;

8.117 Factors affecting reading time for sentences;

11.325 Presentation of numeric data in person-computer dialogue;

11.326 Presentation of text data in person-computer dialogue;

11.327 Presentation of tabular data in person-computer display;

11.328 Graphics in person-computer display;

11.329 Information portrayal in person-computer dialogue;

11.332 Screen layout and structuring in person-computer displays

11.315 Design Recommendations for Query Languages

Table 1. User problems with query languages. (From Ref. 4)

Problem Areas	Comments	Source
Logical quantifiers	Use of logical quantifiers (all, some, none) in the presence of set relations (union, intersection, etc.) is very error-prone.	Ref. 5
Set relations	When sets of elements are related in a complex way, human interpretation of the relationship is often erroneous.	Ref. 5
Logical relations	Disjunction (logical "or") and negation are error-prone constructs. Although this finding is consistent with basic psychological research and is probably generally true, the principal study (Ref. 3) in which it is related to programming and query language design involves an atypical task: the subject must compensate for absence of these constructs in a language by devising a procedural specification using transfer of control.	Ref. 2
Arithmetic relations	Conversion of inequalities (e.g., from "over 50" years old to "51 or more" years old) is error-prone. Also, users tend to use arithmetic relations even with "nominal categories, as "college degree greater than or equal to B.S."	Ref. 2
Semantic confusion of commands	Errors occur when query language has confusable commands, such as COUNT ("how many numbers are there?") and TOTAL ("what is their sum?").	Ref. 2
Use of synonyms for file names, properties, etc.	Users tend to substitute synonymous terms (e.g., "employee" for "personnel" file) that the system may not recognize.	Ref. 5
Misspelling	Spelling errors are common in query formulation. Also, users tend to use an incorrect ending (e.g., "employees" instead of "employee").	Refs. 2, 5, 6
Omission of problem relevant attributes	In formulating complex queries, users frequently omit one or more of the attributes which define the set.	Refs. 2, 6
Contextual referencing	If unconstrained, users tend to make contextual references in queries. However, there is no clear evidence that users fail to adapt to query languages that preclude such references.	Ref. 3

Key Terms

Mixed initiative dialogues; natural language systems; person-computer dialogue; quasi-natural language; query languages; semantic confusion

General Description

Guidelines for the design of query languages have been derived from two types of research: (1) studies of the query behaviors of computer-naive users and attempts to facilitate query formulation in natural languages, and (2) usability studies of specific languages. Although relatively few studies compare across languages or across the entire process, reported errors from these studies provide considerable insight into the kinds of logical constructions and query-language features that represent difficulties for users.

Table 1 displays some known problem areas in the use of query languages. For each problem area, comments and references are provided. A collection of recommendations and guidelines, distilled from the literature (Ref. 1), are presented in Table 2. The recommendations specifically address the previously defined problem areas.

Constraints

A number of questions that are important for designers have not yet been researched (Ref. 3), including:

- Effects of frequency of use on query language choice,
- Amount of instruction required in other languages to achieve the same level of competence,
- Degree of threat that formal query languages pose to potential users,
- The proportion of invalid or incorrect query statements that a user will tolerate prior to rejection of the language or system, and
- Acceptability of a restricted subset of English as query language.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

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Cross References

8.128 Schema theory of memory for text;

11.302 Basic properties of person-computer dialogue;

11.303 Comparison of approaches to person-computer dialogue;

11.304 Major data models in database systems;

11.312 Designing for the casual or infrequent computer user;

11.316 Comparison of query languages: query-by-example, SEQUEL, and algebraic language;

11.320 Error recovery

Table 2. Guidelines for query language design.

General Recommendations

1. Data Organization
   a. Match user's perception of natural organization
   b. Use single representation of data
2. Quantifiers
   a. Minimize use of quantification terms, except "NO and "NONE"
   b. When quantifiers are required
      – Design quantifiers for distinctiveness
      – Provide set of statements for user selection
3. Feedback of Query
   a. Rephrase and display query before execution
   b. Provide override option of this feature for experienced users
4. Abbreviations
   a. Truncate to form abbreviations, except commonly known abbreviations
   b. Three to five characters in length
   c. All abbreviations must be unique
   d. User should know abbreviation logic
5. Dialogue Transaction
   a. System messages should be in directly usable form (e.g., not error code numbers)
   b. Provide prompts or reminders of current state of transaction development
   c. All information for user determination of present system states should be in a single transaction
   d. Periodically recap lengthy sequences of transactions
   e. Information should be in the form immediately needed
   f. Frequently used queries should be easy to conduct
   g. Feedback should include receipt of query and anticipated response time

Special Recommendations: Formal Query Languages

1. Layering
   a. Language features should be partitioned into groups or layers
   b. Easiest layer should stand alone and be intended for causal users
   c. Layers should increase in complexity for more sophisticated users
2. Semantic Confusion
   a. Avoid operators such as "or more" and "or less"
   b. Operators should be given semantically similar names
   c. Names of operators should be unique and self-explanatory
3. Term Specificity
   Global terms are not recommended for beginning users, except where globally described data are retrieved together frequently

Special Recommendations: Informal Query Languages

1. Clarification Dialogue
   a. System should clarify poorly stated queries rather than reject them
   b. Systems should guide user in formulation of properly stated query
2. Quasi-Natural Language
   Requires narrow and well-defined systems task

11.316 Comparison of Query Languages: Query-by-Example, SEQUEL, and Algebraic Languages

Key Terms

Algebraic language; person-computer dialogue; query languages; SEQUEL; training; Zloof's query-by-example language

General Description

Various query languages have been developed for accessing computerized information. A comparison of the relative learning and application capabilities of Zloof's query-by-example language (Ref. 4), SEQUEL, a structured English query language (Ref. 1), and a variation of Codd's algebraic language (Ref. 2) indicates that query formulation is aided more by the tabular format and the lower ambiguity of query-by-example than by the other two languages (Table 1). Query-by-example yields the fewest less-than-chance confidence ratings (Fig. 1) and the shortest mean time per query.

Applications

Selection of query languages for casual or infrequent users; query language selection for systems where training time is severely limited; prediction of needs for query-in-depth user aids.

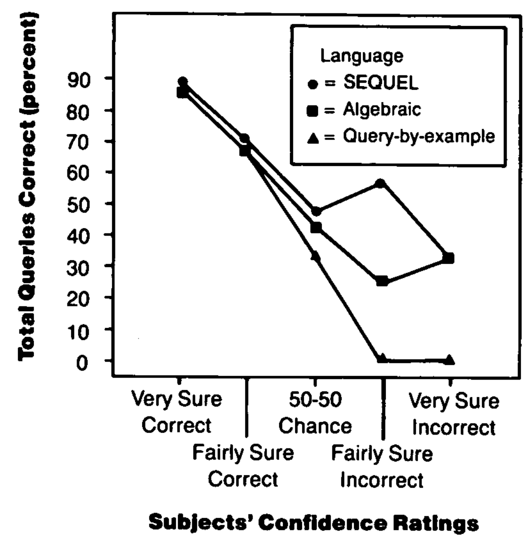

Figure 1. Query correctness as a function of confidence ratings. (From Ref. 3)

Methods

Test Conditions

- Twenty-question exams translated into three database query languages
- Exams provided sample database and sample queries to the database
- Subjects trained in languages by review of examples and instructor feedback

Experimental Procedure

- Between-subjects design
- Independent variable: query language
- Dependent variables: training time, exam time, percent correct queries, subjective ratings of confidence
- Subject's task: interpret exam questions into query language and mark confidence level for answer on 5-point scale (see Fig. 1)
- 7 subjects for query-by-example, 17 subjects for SEQUEL, and 13 subjects for algebraic language; all subjects were college undergraduates

Experimental Results

- Subjects are more sure of their answers and mean time per query is lower for query-by-example.

Variability

- There is no significant difference in mean exam time and mean correct queries among the three languages because of large standard deviations.

Constraints

- The query languages compared differ considerably in basic philosophy and in details of dialogue.
- The present study addressed only part of the query process, encoding the query. The overall process includes: (1) information need, (2) question formulation, (3) approach planning, and (4) query encoding.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

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Cross References

11.301 Steps in dialogue design;

11.315 Design recommendations for query languages

Table 1. Comparison of three query languages: time, accuracy, and subject confidence. (From Ref. 3)

	Query by Example	SEQUEL	Algebraic Language
Training time (hours:minutes)	1:35	1:40	2:05
Mean total exam time (minutes)	23.3	53.9	63.3
Mean correct queries (percent)	75.2	72.8	67.7
Mean time/query (minutes)	0.9	2.5	3.0
Mean confidence/query (1 = highest and 5 = lowest)	1.6	1.9	1.9

11.317 Data Entry Displays

Table 1. Guidelines for design of data entry displays. (From Ref. 2)

Design Objectives

1. Establish consistency of transactions
2. Minimize input actions
3. Minimize memory load on user
4. Ensure compatibility of data entry with data display
5. Provide flexibility of user control of data entry

Minimal Keying for Character Entry

1. Alphanumeric entries should be a single stroke of labeled keys
2. Minimize double-keying for special characters
3. Automatic entry of leading zeros should be optional
4. Eliminate distinction between single and multiple blanks

Implicit Prompting for Data Field Delineation

(Good)	(Bad)
LICENSE NUMBER: _ _ _ _ _ _ _ _ _ _ _ _	ENTER LICENSE NUMBER:
MAKE:	ENTER MAKE (14 characters):
YEAR/MODEL:.	ENTER YEAR/MODEL (11 characters):

1. Mark fields with special characters
2. Visually indicate fixed or maximum acceptable entry
3. Distinguish required and optional entries
4. Automatically justify entry and remove unused underscores
5. Provide tab keying between fields

Logical Format of Data Fields

1. Data entry display should be compatible with output display
2. Data entry display should match source document format
3. Entry should follow logical sequence if no source document exists
4. User should not have to enter data twice.

Clear Labeling of Data Fields

(Good)	(Bad)
Week: _______ Month: _______ Year: _______	DACODE: _ _ _ _ _ _ _ _ _ _ _ _ _ _
Social Security Number: _____ - _____ - _____	SSAN: _ _ _ _ _ _ _ _ _ _ _ _ _ _ _
Speed limit: ________ MPH	LIM: _ _ _ _ _ _ _ _ _ _ _ _ _ _ _ _
Distance: ___________ (km/hr) ___________	DIST (4 chars and unit) _ _ _ _ _ _ _
Cost: $_____________	COST: _ _ _ _ _ _ _ _ _ _ _ _ _ _ _

1. Use agreed terms, codes, or abbreviations only
2. Separate label from field with an exclusive punctuation character
3. Include data format cues where applicable
4. Display fixed measurement units in label
5. For variable measurement units, provide alternatives and space for user entry
6. Use units of measurement that are familiar to user
7. Do not require user to do any data conversions

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Computer initiated dialogue; data displays; field labels; guidance messages; person-computer dialogue; sequence control

General Description

User-composed data entry provides a more flexible means of input than some of the more limited dialogue types, such as menu selection. Greater variability in user performance (input and error rates) results from this flexibility, especially among infrequent and novice users. Table 1 provides a set of guidelines for selection of codes, design of data fields, and use of labels for optimizing user performance in data entry tasks.

Applications

Data entry tasks; form-fitting dialogue; computer-initiated dialogue.

Constraints

- Guidelines may not be generalizable to all applications.
- Some user-controlled flexibility may increase efficiency, such as user pacing of data input, control of input sequence, or definition of default values.
- Design of data-entry transactions is highly dependent on hardware design/selection.
- Guidelines may not be based on data from empirical research.

Key References

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Cross References

11.312 Designing for the casual or infrequent computer user;

11.313 System response time and the effect on user performance and satisfaction;

11.319 Sequence control in person-computer dialogue;

11.325 Presentation of numeric data in person-computer dialogue;

11.327 Presentation of tabular data in person-computer display;

11.330 Abbreviations and acronyms in person-computer dialogue

11.318 Comparison of Input Time and Errors for Point-In and Type-In Data Entry

Key Terms

Input error; joysticks; keyboards; light pens; rolling ball; typing

General Description

Measurements of the relative efficiency of type-in (keying) and point-in (pointing) data-entry methods in terms of input speed and accuracy indicate that input task, word density, and typing ability all influence input time as well as number and kinds of errors. Table 1 provides comparisons on input time for all levels of these variables. Tasks consisting of (1) searching displays for words and (2) typing words not displayed take longer to perform than either tasks consisting of searching and detecting displayed words or simply typing the words. Entry time increases with lower typing skills and higher word densities.

Error frequencies, categorized by type, are presented in Table 2. Statistical comparison of errors for all levels of the main variables and for error type are presented in Table 3.

Applications

Selection of input devices for data-entry tasks in which entry time or errors are critical.

Methods

Test Conditions

- Simulated data-entry console consisted of IBM electric typewriter, two rear-projection source data screens, observer ready light, and a simulated data-entry knob
- Randomized lists of unique three to seven character words (printed console display formats and photographically projected source data sets)
- Five-word (data) arrangements: vertical, semi-vertical, proportional, semi-horizontal, horizontal
- Four density levels: 6, 10, 14, 18 words per list
- Six input tasks (point-in three and type-in zero words, point-in two and type-in one word, point-in one and type-in two words, point-in zero and type-in three words, point-in all three words, type-in all three words with yellow and red coloring, respectively, to indicate last two types of input tasks
- Typewriter (keypunch device) located on either left or right of subject

Experimental Procedure

- Independent variables: word (data) arrangements, number of words in list (word density), input task, sex of subject, relative location of keypunch device, subjects' typing speeds
- Dependent variables: input time (elapsed time per trial) and error scores (incorrect transcription of source data words coincident with input task)
- Subject's task: read source word list from display screen; source words appearing on printed console display format were marked (point-in response), and unlisted words were input on keypunch device (type-in response)
- 24 subjects with varied typing ability (Good: 32-73 words per min; Fair: 17-32 words per min; Poor: 15-17 words per min)

Experimental Results

- Word arrangement and position of keyboard have no influence on performance.
- Input time decreases (1) as number of point-in words decreases in mixed tasks, (2) as word density decreases, and (3) as typing skills improve.
- Detection errors are most common (41% of all errors), followed by typographical (22.6%), redundancy (16%), misperception (15.6%), substitution (3.3%), and omission (0.9%).
- Mean error in the point-all words task is smaller than

Table 1. Mean input time in sec for different levels of input task, word density, and typing ability. (From Ref. 1)

(a) Input tasks	
Point all	6.58]
Point 3, type 0	7.13]
Type all	7.50]
Point 2, type 1	10.32
Point 1, type 2	12.34]
Point 0, type 3	12.57]
(b) Word density	
Six words	9.87
Ten words	11.13
Fourteen words	13.20
Eighteen words	14.74
(c) Typing ability	
Good	7.33
Fair	8.37]
Poor	8.76]

Note: Levels of the factors enclosed by brackets are not significantly different at $p < 0.01$.

Table 2. Frequency of point-in and type-in errors listed by error type. (From Ref. 1)

Classes and Types of Errors	N Errors	% of Total Errors
Point-in errors		
Detection	300	41.0%
Substitution	24	3.3%
Omission	3	0.4%
Total point-in errors	327	45.1%
Type-in errors		
Omission	4	0.5%
Redundancy	116	16.0%
Misperception	113	15.6%
Typographical	164	22.6%
Total type-in errors	397	54.9%
Total Errors	724	100.0%

under all other task conditions. Mean error under the point-zero type-three and type-all words tasks is significantly lower than the mean error for the remaining input tasks.

- Significantly fewer errors are made under the six-word density level than under the other three density levels (10, 14, or 18 words), and more errors are committed under the 18-word level than under the other three density levels.
- There is no significant difference in input time between point-all and type-all methods, but the input error rate (one error per every 133 words entered) for the point-all task is one-seventh the error rate (one error per every 18 words entered) of the type-all task.
- Data input by the type-in method results in typographical and misperception errors. Both of these error types are eliminated when using the point-in method.
- An increase in word density inhibits input performance by increasing input time and error rate. The bulk of the error increase is the result of a large increase in detection errors.
- Comparison of the point-all and type-all conditions with the three actual mixed input tasks shows that the factor of certainty of input method (i.e., more information) enhanced performance.

Variability

Analysis of variance used to test significance.

Constraints

- Performance in mixed point-in/type-in tasks may increase if subject is familiar with the words contained in the formats.
- Visually separate and partial feedback displays, as a function of input-task type, were used; a unified feedback display may result in better performance.

Key References

*1. Earl, W. K., & Goff, J. D. (1965). Comparison of two data entry methods. *Perceptual and Motor Skills*, *20*, 369-384.

Cross References

11.317 Data entry displays;

12.407 Conventional versus membrane keyboards;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.410 Keyboards and keysets: effects of key size, force, displacement, and feedback on keying performance;

12.412 Control type, location, and turbulence: effect on data entry performance;

12.415 Selection of data entry devices: ten-button keyset, matrix keyboard, vertical levers, and rotary selectors

Table 3. Mean error scores per subject for different levels of input task, levels of word density, and type of error. (From Ref. 1)

(a) Input tasks	
Point all	0.54
Point 0, type 3	3.13]
Type all	4.00]
Point 3, type 0	7.13]
Point 2, type 1	7.42]
Point 1, type 2	7.96]
(b) Word density	
Six words	4.25
Ten words	5.63]
Fourteen words	6.33]
Eighteen words	9.96
(c) Error types	
Omission	0.29]
Substitution	1.00]]
Redundancy	4.70]]
Misperception	4.83]]
Typographical	6.83]
Detection	12.50

Note: Levels of the factors enclosed by brackets are not significantly different at $p < 0.01$.

11.319 Sequence Control in Person-Computer Dialogue

Key Terms

Control flexibility; interactive systems; person-computer dialogue; sequence control; user initiative

General Description

The logic and means of input and output linkage into coherent transactions, as well as control of interactive transactions, should be designed to:

1. Maintain consistency of control actions,
2. Minimize control actions and user memory load,
3. Be compatible with user and task needs, and
4. Allow flexibility of control by the user.

The degree and type of user control must be mediated by the type of task and the characteristics of the user. As a general rule, however, user control is preferable to system (computer) control.

Flexibility is a desirable attribute of sequence control, provided the designer heeds several cautions: (1) Errors in sequence control should be expected, as are data-entry errors. Therefore, error-correction mechanisms must be included for both system-detected and user-detected errors. (2) Total flexibility may not be appropriate for all types of users. Maximum flexibility may be appropriate for experienced or professional users, but it may confuse novice or infrequent users. Failure to provide appropriate levels of flexibility to match the various levels of users will prove frustrating to the users for whom the system is not designed. This issue can be addressed partly in the selection of the type of dialogue employed. Options such as multiple dialogue types or user selectable amounts of user control should be considered. These issues are considered in the guidelines provided in Table 1.

Constraints

- The guidelines provided for sequence control may not have been empirically validated.

Key References

1. Smith, S. L. (1980). *Requirements definition and design guidelines for the man-machine interface in C³ system acquisition* (ESD-TR-80-122). Bedford, MA: MITRE Corp. (DTIC No. ADA087258)

*2. Smith, S. L., & Aucella, A. F. (1983). *Design guidelines for the user interface to computer-based information systems* (ESD-TR-83-122). Bedford, MA: MITRE Corp. (DTIC No. ADA127345)

Cross References

11.301 Steps in dialogue design;

11.303 Comparison of approaches to person-computer dialogue

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Selected guidelines for design of sequence control.

User Considerations

1. Minimize user actions
   a. Simplify control actions to maximum extent
   b. Design for minimum number of required control entries consistent with user abilities
2. Match ease of sequence control with desired ends
   a. Frequent or urgent actions—easy and quick control
   b. Potentially destructive actions—distinctive actions under explicit user control
3. Match control to level of user skill
   May require mixed dialogue or entry stacking option
4. Require explicit user actions
   a. Computer should not interrupt user entries until conclusion
   b. Routine actions can benefit from computer control
5. Permit initiative and control by user
   a. Anticipate all possible user actions and consequences
   b. Provide appropriate options for each potential user action
   c. Avoid "dead-ends" in dialogues
   d. Allow user to interrupt, defer, or abort transaction sequences
6. User pace sequence control
   Design for user's needs, attention span, and time available
7. Prevent interference between simultaneous users

Logic Considerations

1. Design consistent control actions throughout a system
2. Control actions should be independent of prior actions
3. Base-linked transaction sequence on user task analysis
   "Logical unit" of user, not logical unit of computer system, should determine transaction sequence
4. Establish consistent terminology for instructional materials, online messages, and command terms
5. Offer active options only

Language Considerations

1. Base choice of dialogue and design of sequence control on user and task characteristics
   a. Question-and-answer dialogue: for routine data-entry tasks, when data items are known and their ordering can be constrained, when the user has little or no training, and when computer response is expected to be moderately fast
   b. Form-filling dialogue: when some flexibility in data entry is needed, such as the inclusion of optional as well as required items, when users have moderate training, and/or when computer response may be slow
   c. Menu selection: tasks such as scheduling and monitoring that involve little entry of arbitrary data, when users have relatively little training, and when computer response is expected to be fast
   d. Function keys: tasks requiring only a limited number of control entries, or in conjunction with other dialogue types as a ready means of accomplishing critical entries that must be made quickly without syntax error
   e. Command language: tasks involving a wide range of user control entries, when users are highly trained in the interests of achieving efficient performance, and when computer response is expected to be relatively fast
   f. Query language: specialized sub-category of general command language for tasks emphasizing unpredictable information retrieval (as in many analysis and planning tasks), with moderately trained users and fast computer response
   g. Graphic interaction: supplement to other forms of human-machine dialogue when special task requirements exist; effective implementation of graphic capabilities requires very fast computer response

Input/Output Considerations

1. Computer response time should match transaction
   Faster response for those perceived by user to be simpler
2. Entries should not be paced by computer response delays
   a. When delays are unavoidable, keyboard should automatically lock
   b. Following lockout, computer readiness should be signaled to user
   c. User should be provided with means of aborting transaction during lockout
3. Provide unambiguous feedback for control entries
   a. Signal completion of processing
   b. Unambiguous feedback can be immediate execution, change in state, or acceptance/rejection message
4. Design sequence control features to be distinctive in position or format

11.320 Error Recovery

Key Terms

Directional guidance; error correction; error messages; error recovery; person-computer dialogue; prompting

General Description

Although 80% of all keying errors are detected consciously, person-computer dialogue design should aid the user in correcting and recovering from system-detected errors. Recovery techniques should consider feedback, directional guidance, temporal and spatial proximity, opportunity for immediate correction, and availability of relevant documentation. The failure to consider any of these has varying negative impact on the probability of correct and rapid recovery from an error.

Table 1 incorporates these principles into guidelines for error detection, error message design, and error correction. When little attention is given to these considerations, system performance degrades due to excessive user time spent searching for and correcting errors. Error recovery mechanisms should be designed to maximize the educational/training aspect, with the intention of reducing future recurrences. The level of effort required to correct errors should be minimized to permit maximum user concentration on the problem-solving aspects of error recovery.

Constraints

- The specific procedures for handling user-input errors and what to communicate for effective error recovery have not been systematically researched.

Key References

*1. Engle, S. E., & Granda, R. E. (1975). *Guidelines for man/display interfaces* (00.2720). Poughkeepsie, NY: IBM.

2. Hendricks, D., Kilduff, P., Brooks, P., Marshak, R., & Doyle, B. (1982). *Human engineering guidelines for management information systems* (DOD-HDBK-761). Philadelphia, PA: Naval Publications and Forms Center. (DTIC No. ADE750934, announcement only)

Cross References

11.310 Interface design principles derived from human error analyses;

11.317 Data entry displays;

11.319 Sequence control in person-computer dialogue

Boff, K. R., & Lincoln, J. E. Engineering Data Compendium: Human Perception and Performance. AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Guidelines for error detection, message design, and correction.

Error Detection

1. Users should be able to stop and return to previous levels of a multi-level control process at any point in a sequence as a result of user-detected error.
2. Rejected inputs should result in an error message with highlighting of the erroneous portion.
3. Batched or stacked strings of entries should be processed (executed) to the point of error and then an error message should be sent.
4. Error messages should be provided as soon as possible after detection by the system.
5. For multiple errors, the number of errors detected and their locations should be displayed until they are corrected.
6. Errors made while correcting other errors should result in new error messages.
7. User-input errors should be minimized through internal software validation of entries, such as detection of numerics entered in alpha fields.

Error Message Design

1. System-detected errors should result in messages providing as much diagnostic information and remedial action as can be inferred reliably from the error condition.
2. Error messages should reflect the user's point of view of what is needed for recovery.
3. All error messages should indicate:
   a. location of error
   b. nature of error
   c. one or more ways to recovery or where to find out how to recover.
4. Error messages should appear as close as possible to the erroneous entry.
5. Error message should be understandable and non-threatening to user (avoid computer-jargon, humorous, or condemning messages).
6. User should be able to select the amount of detail contained in error messages; two levels of messages will be sufficient for most cases.

Error Correction

1. An easy means of correcting erroneous entries should be provided.
2. When an error has occurred, the system should allow immediate correction.
3. A user should not have to re-enter an entire line because of an omission or misspelling of one word.
4. Lines of input should be alterable during as well as after entry.
5. Users should be able to stop and return, at any point, to previous levels of multi-level control processes.

11.321 Design and Control of Cursors

Table 1. Selected design considerations for position-designation cursors.

Task Type (as Sole or Primary Dialogue Mechanism)	Design Considerations	Principal Control Device
Continuous positioning		
(a) Rough	(a) At least 20-30 cm displacement in 0.5 sec	Continuously operable controls: 1. Thumbwheel 2. Joystick 3. Mouse
(b) Fine	(b) Options include: 1. Point designation (like cross-hairs or gunsight) 2. Incremental stepping 3. Large control/display ratios 4. Selectable step-size	
Sequential positioning	User action for cursor movement should be minimized	Programmable tab keys
Positioning and item selection	Target area should be as large as consistently possible: label area plus half character distance around label	Direct pointing types: 1. Lightpen 2. Touch screen Highlighting selected item
Keyed data entry	Minimize cursor positioning movements and search time	Integral to keyboard: 1. Function keys 2. Joystick Automatic positioning
More than one task using multiple cursors	Cursors should be visually distinctive Minimize use of multiple cursors to reduce user confusion Single device control: Indicate to user which cursor is being controlled Multiple device control: Controls should be compatible in operation	Select by above listed types

Key Terms

Cursor control; person-computer dialogue; position designation; prompting

General Description

Cursors provide position designation for information to be entered or selected by the user. Table 1 provides design considerations for five types of tasks in person-computer dialogue. In general, movable cursors should be designed to:

1. Be located easily at random positions and be tracked easily while moving.
2. Not interfere with the symbol/position being marked.
3. Not distract or impair searches for other displayed information.
4. Have a consistent starting point within frame as well as between frames.
5. Remain stable (drift-proof) until positioned or repositioned.
6. Be box or block-type with optional 3-Hz blinking.

Applications

Position designation for user inputs and information location or selection markers.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Design of cursors and control devices is a function of the task performed by the user.
- Variable character size on display requires variable step size of incremental stepping cursor. Step size should be consistent in all directions of movement.

Key References

*1. Hendricks, D., Kilduff, P., Brooks, P., Marshak, R., & Doyle, B. (1982). *Human engineering guidelines for management information systems*. Alexandria, VA: U.S. Army Material Development and Readiness Command.

*2. Smith, S. L., & Aucella, A. F. (1983). *Design guidelines for the user interface to computer-based information systems* (ESD-TR-83-122). Bedford, MA: The MITRE Corp. (DTIC No. ADA127345)

Cross References

11.331 Prompting in person-computer dialogue;

12.422 Comparison of cursor control devices

11.322 On-Line Documentation

Key Terms

Error messages; off-line documentation; on-line documentation; person-computer dialogue

General Description

When off-line documentation, on-line documentation, and help sequences are designed according to a single "style," they typically do not provide an appropriate level of information for both novice and experienced users. Inclusion of on-line message layering or selectable message levels can be used successfully to meet various needs. Table 1 presents general guidelines for design of documentation and help sequences.

Table 2 describes different approaches to designing online help for programmers and non-programmers. These approaches were empirically compared (Ref. 3), and the results indicate that seemingly superficial differences in message style have a significant effect on novice-user performance, which is better when a message style designed for non-programmers is used.

Methods

Test Conditions

- Typical, fully automated office task involving computer file manipulation: creation and distribution of reports from prewritten material
- On-line help messages (two versions as described in Table 2) presented on DEC VT100 terminal under DEC VAX/VMS operating system version 2.3

Experimental Procedure

- Independent variable: style of help messages and error messages
- Dependent variables: number of commands and time consumed for task completion, errors, and accessing of system information; level of user satisfaction
- 32 computer novices as subjects

Experimental Results

- More subjects complete the task using the "non-programmer" style (93%) than using the "programmer" style (20%). Also, mean task-completion time is shorter for subjects using the "non-programmer" style (52 versus 84 min).
- Performance with the "non-programmer" style is significantly better than for the "programmer" style: higher task score, more commands per min, fewer references to off-line documentation, and fewer questions asked.
- Total number of commands generated with the "non-programmer" style is not greater than with "programmer" style, but they are produced almost twice as quickly (1.95 versus 0.99 per min).
- Fewer erroneous commands are generated with the "non-programmer" style than with the "programmer" style. Less total time (7.4 versus 33.4 min) is spent generating erroneous commands with the "non-programmer" versus "programmer" style.
- Help commands are used more with the "non-programmer" style.
- Subjects prefer the "non-programmer" style over the "programmer" style. Reasons for the "non-programmer" preference included greater ease-of-use and ease-of-learning, less frustrating, less complex, less confusing, greater flexibility and personal control, more friendly, more on-line help, and better error messages.

Table 1. Selected guidelines for design of on-line and off-line documentation. (From Ref. 7)

Help and Documentation
On-line documentation, off-line documentation, and help sequences should use consistent terminology.
Off-Line Documentation
All error messages should be listed and explained in the off-line system documentation.
Every non-menu **frame** should contain a reference to a specific section of off-line documentation to provide a ready source of explanation.
On-Line Documentation
After accessing help, the user should be provided with an easy way to return to the main dialogue.
On-line access to help facilities should be provided for each command.
All error messages should be listed and explained in the on-line help sequences.
A dictionary of abbreviations and codes should be available on-line.
On-line access to a list of system capabilities and subsystems should be provided. By showing the system components, options, and structure, the on-line reference capability permits the user to understand and use the system effectively.
When possible, natural language, rather than a hierarchic menu, should be used to invoke on-line documentation.
If more details are needed, the user can ask for a continuation. Successive levels of the HELP request can go into greater detail.

Constraints

- Only novice users were included as subjects.
- Guidelines presented in Table 1 may not be empirically based.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Brown, C. M., Burkleo, H. V., Mangelsdorf, J. E., Olsen, R. A., & Williams, A. R., Jr. (1981). *Human factors engineering criteria for information processing systems*. Sunnyvale, CA: Lockheed.

2. Galitz, W. O. (1981). *Handbook of screen format design*. Wellesley, MA: Q.E.D. Information Sciences.

*3. Magers, C. S. (1983). An experimental evaluation of on-line help for non-programmers. In A. Janda (Ed.), *Proceedings of CHI-83 Human Factors in Computing Systems* (pp. 1-10). New York: Association for Computing Machinery.

4. Miller, L. A., & Thomas, J. C., Jr. (1976). *Behavorial issues in the use of interactive systems* (RC 6326). Yorktown Heights, NY: IBM.

5. Parrish, R. N., Gates, J. L., & Munger, S. J. (1981). *Design guidelines and criteria for user/operator transactions with battlefield automated systems. Vol. IV. Provisional guidelines and criteria (ARI-TR-537-Vol-4)*. Alexandria, VA: Army Research Institute. (DTIC No. ADA115892)

6. Pew, R. W., & Rollins, A. M. (1975). *Dialog specification procedures* (rev. ed.) (Rep. No. 3129). Cambridge, MA: Bolt, Beranek, and Newman.

*7. Williges, B. H., & Williges, R. C. (1984). Dialogue design considerations for interactive computer systems. In F. A. Muckler (Ed.), *Human factors review: 1984*. Santa Monica, CA: Human Factors Society.

Cross References

11.312 Designing for the casual or infrequent computer user;

11.320 Error recovery;

11.331 Prompting in person-computer dialogue

Table 2. Differences between the on-line help modified for non-programmers and the system for programmers. (From Ref. 3)

Programmer's System	Non-Programmer's System
HELP command only	HELP command and HELP key
Keyword-indexed help	Context-sensitive help
Rigid rules for forming HELP commands	More lenient rules for forming correct HELP commands
Mostly reference Help	Tutorial Help and reference Help
Uses computer jargon	Reasonably jargon-free or jargon explained
Uses mathematical notation	Uses examples
Error messages	Suggested correction messages
No feedback when command correct	Positive feedback messages confirm correct commands
Unlimited access to all commands	Limited number of commands available to novices
Precise command names required	On-line dictionary of command synonyms
Lengthy Help "scrolls" on screen	Help in short frames that fill two-thirds of screen
Computer-oriented Help	User-task-oriented Help

11.323 Aids to Person-Computer Problem Solving

Key Terms

Decision aiding; decision making; goal setting; lockout; problem definition; problem solving

General Description

Reference 1 has defined problem solving as building a bridge or connection between a set of "knowns" (e.g., an arithmetic problem, or set of characters in a story) and a set of "unknowns" (e.g., the problem solution, or the goals of the characters). In the arithmetic problem example, the connection between knowns and unknowns is generated; in the story example, the connections are only recognized. The problem-solving aids discussed in this entry are for situations in which the connections must primarily be generated.

Problem-solving behavior can be classified on three dimensions (Fig. 1): whether abstraction occurs, whether search behavior is necessary, and whether the behavior is data-driven or conceptually driven. When the additional step of abstraction is part of the problem-solving processes, the initial problem is reformulated into a more general form and a solution is sought for the new problem statement. When a search process is involved, the problem solver has to generate and choose from among a set of alternative solutions rather than directly applying all or part of a solution that has already been developed. Finally, data-driven behavior is guided by aspects of the particular problem being solved (e.g., in medical diagnosis); conceptually driven behavior is guided by the problem-solver's experiences with similar domains (e.g., system design).

Figure 1 relates 15 problem-solving aiding mechanisms (described in Table 1) to the types of problem-solving behavior where they are most effectively applied. Table 1 describes each of the aiding mechanisms and includes additional relevant information; Ref. 1 lists sources of more information for each mechanism.

Aiding Mechanism	Behavior Type: Abstraction	No Abstraction	Search	No search	Data-driven	Conceptually driven
Alternative evaluation		•	•		•	
Alternative generation		•	•			
Automatic action execution				•		
Automatic takeover*						
Backtracking		•	•			
Better weighting of unreliable data					•	
Change of problem representation	•					•
Decision consistency improvement					•	
Decision strategy improvement	•					•
Decomposition and recombination	•					
Disruption of psychological set*						
Extended memory		•	•	•		•
Lockout*						
Rapid trial-and-error		•	•			
Strategy capture					•	

Figure 1. Relationship of aiding mechanisms to types of problem-solving behavior. For asterisked items, relationship with behavior type was not identified in original source. (From Ref. 1)

Constraints

- The aiding mechanisms discussed in this entry are primarily for solution-generation tasks rather than solution-recognition tasks.
- The experience of the user and the type of specific task affect the problem-solving behavior that is used.
- More than one type of behavior may occur for any one task.
- The information in this entry is at a general level rather than in the form of specific guidelines.

Key References

*1. Ramsey, H. R., & Atwood, M. E. (1979). *Human factors in computer systems: a review of the literature* (SAI-79-111-DEN). Englewood, CO: Science Applications, Inc. (DTIC No. ADA075679)

Cross References

7.901 Characteristics of humans as decision makers;

11.301 Steps in dialogue design;

11.305 Techniques for modeling interactive systems;

11.324 Voice versus written communications between users for problem solving

Table 1. Types of problem-solving aids that may be applied in situations where problem solutions must be generated (rather than recognized). (From Ref. 1)

Aiding Mechanism	Description	Comments
Alternative Evaluation	These aids may either automate the user's evaluation criteria, require use of established criteria, or stimulate the results of actions that do not have well established evaluation criteria.	Except for aids that automate the user's evaluation criteria, these aids are task-specific. Most useful if the task is not well defined or if a large number of evaluation criteria need to be considered.
Alternative Generation	These aids are primarily used to generate alternatives that the user would not normally consider or, for extremely well-defined tasks, to present algorithmically determined alternatives.	Except for well-defined task domains, where they may have very little impact, they are difficult to construct. Can be cost-effective for training applications, but generally are of limited use in complex problem-solving tasks.
Automatic Action Execution	Such aids permit the user to name the desired action without explicitly carrying out the steps involved in its execution.	Most useful when the results of applying an action do not impact subsequent problem-solving actions. If this is the case, the user may need sophisticated alternative evaluation heuristics.
Automatic Takeover	This type of aid functions as an automated decision maker that is able to select alternative actions on the basis of prior observations of the human decision maker's behavior. Although allocation of control to this aid occurs automatically, whenever some criterion or correspondence between predicted and observed human behavior is reached, voluntary turnover of control is also possible.	Although demonstrated to be effective in some contexts (e.g., control tasks), the range of tasks in which this is appropriate is not well understood. User acceptance may be low and should be carefully examined.
Backtracking	Such an aid allows the problem solver to "undo" the effects of recent actions and return to an earlier state of the problem-solving process without actually starting over.	Useful in task where it is possible to "undo" recent actions. Can improve performance at relatively little development cost.
Better Weighting of Unreliable Data	This aid re-codes low-fidelity data into a form that is more readily useable by the problem solver.	Depends on the ability to accurately recode low-fidelity data.
Change of Problem Representation	Typical implementations of this aid present problems as isomorphic variations of more standard problem representations. It is intended that this will aid the problem solver in selecting an appropriate and efficient problem formulation.	Most useful in well-understood tasks. An inappropriate representation may seriously degrade performance.
Decision Consistency Improvement	This type of aid assists the users in applying their own decision strategies consistently in cases in which these strategies are complex.	Useful for expert problem solvers in well-defined tasks. Including sufficient versatility to adapt to individual users may be difficult.
Decision Strategy Improvement	Such aids assist the user in applying problem-solving techniques that would not normally be considered or known.	Useful in well-defined tasks in which optimal, or near optimal, problem-solving techniques are known, or in tasks in which general heuristics, such as problem reduction, are applicable. Requires detailed knowledge of the task.
Decomposition and Recombination	This type of aid allows the user to divide the original problem into sub-problems. The solutions of the various sub-problems are then combined into a solution to the original, larger problem.	Useful only if a task can be decomposed into independent sub-problems. Requires a good understanding of the task.
Disruption of Psychological Set	Such an aid is intended to disrupt any bias or "sets" that the user may employ and thereby stimulate more creative, or novel, problem-solving attempts.	Potentially useful, but may disrupt an *appropriate* "set".
Extended Memory	This aid allows the user to store and retrieve problem-relevant information. This information may initially be generated by the user or by other problem-solving aids, for alternative generation and evaluation.	Very useful in almost all tasks. Success is related to the ease of retrieval from external memory.
Lockout	In an interactive problem-solving situation, this technique restricts the problem solver's access to the computer for some time after the presentation of the results from the current request for information.	Although demonstrated to be effective in some contexts, user acceptance was low. The tradeoff between user performance and user acceptance should be carefully considered.
Rapid Trial-and-Error	This aid allows the user to rapidly and easily examine the consequences of alternative action by simulating their application.	Easily implemented in well-defined tasks. May offset inadequacies in decision strategy improvement aids.
Strategy Capture	These aids attempt to model and predict the user's behavior. Strategy capture is generally used in conjuction with other aids, such as automatic takeover or alternative evaluation.	A prerequisite for developing automatic takeover aids. Best suited to tasks that allow algorithmic, rather than heuristic, strategies.

11.324 Voice Versus Written Communications Between Users for Problem Solving

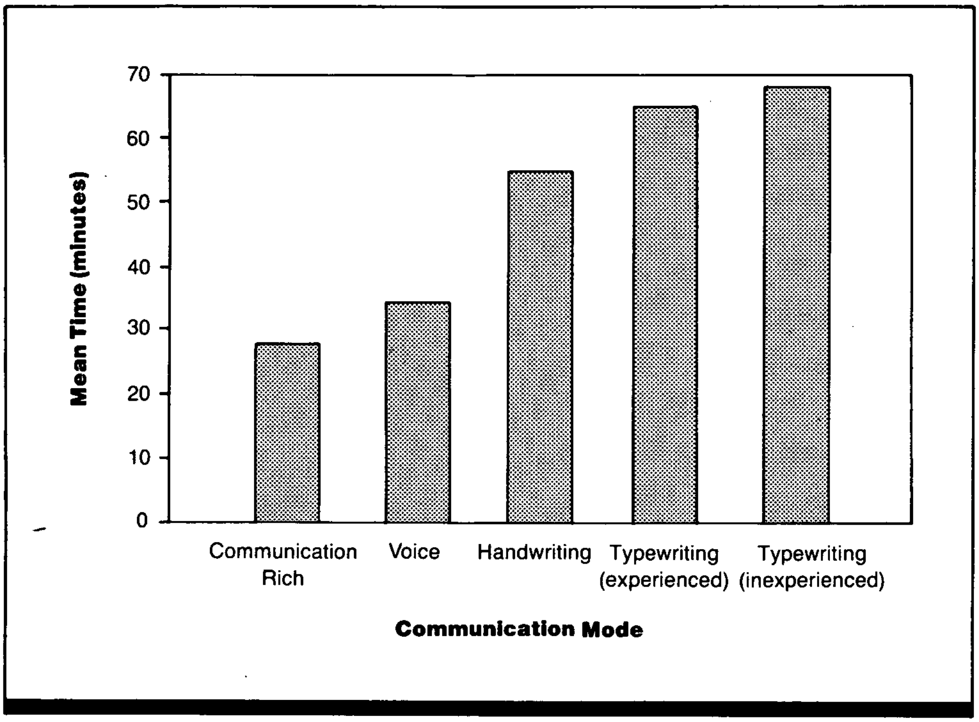

Figure 1. Problem-solving time for five communication modes. (From Interactive human communication by A. Chapanis. Copyright © 1975 by Scientific American, Inc. All rights reserved.)

Key Terms

Decision aiding; keyboard input; natural language systems; problem solving; voice signals

General Description

When two people must communicate to solve a problem, solutions are achieved more quickly with voice communications than by handwriting or typewriting. However, these communications have almost no syntactic structure, and subjects using the voice modes generate eight times as many words as subjects using the writing modes.

Applications

Designers of person-computer dialogues, particularly those responsible for constraining the behavior of the human through software syntax, should be aware of the communications tendencies of humans when a syntax is not imposed. Designers or advocates of the "natural language interface" concept should be aware of the "unruly" verbal tendencies of human problem solvers.

Methods

Test Conditions

• Pairs of subjects solved problems by communicating in one of five conditions: (1) face-to-face (communication rich), (2) voice without vision, (3) handwriting, (4) typing (experienced typists), or (5) typing (inexperienced typists); all communications were observed and recorded

• Problems required working together (e.g., equipment assembly when one subject had the assembly directions and the other had the parts)

Experimental Procedure

• Independent variable: communication condition

• Dependent variables: time to solve the problem, number of total messages per subject, number of total sentences, number of total words, number of different words, ratio of difficult words to total words, number of words per min during communications, number of words per message, number of words per sentence, percentage of sentences that were questions

• Subject's task: communicate with other subject to solve problem

• Unknown number of high school and college students (experienced and inexperienced typists)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

• Time for solving problems is shown in Fig. 1 for the five communications types. The voice modes yield faster problem solution times than do handwriting or typing. Despite the arguments for nonverbal communication, the time taken to solve problems by voice alone is only slightly greater than with face-to-face communication (which allowed pointing and other non-verbal cues).

Table 1 lists results for seven measures of communication for each of the five experimental conditions. The results indicate that problem solving by voice takes the least time, but is wordier than other modes of communication. In general, all of the communication modes studied involved rather "unruly" adherence to grammatical, syntactical, and semantic rules.

Constraints

• These data apply to human-computer dialogue only indirectly and by inference.
• The studies used only pairs of subjects.
• The data do not indicate the capability and limitations of humans to comply with syntactic structure when required.
• Individual differences in imposing syntax on communications are not described.
• The tendency to avoid language structure in communications that is found in these studies is not specific enough to formulate predictions about the frequency and type of noncompliance to be expected when a rigid syntax is imposed.

Key References

*1. Chapanis, A. (1975). Interactive human communication. *Scientific American, 232*, 36-42.

Cross References

7.901 Characteristics of humans as decision makers;

8.106 Visual language processing of words and pictures;

8.301 Effect of type of test material on speech intelligibility;

11.301 Steps in dialogue design;

11.317 Data entry displays

Table 1. Problem solving time for seven measures of communications.

				Typewriting	
	Communication Rich	**Voice**	**Handwriting**	**Experienced Typists**	**Inexperienced Typists**
Solution time (min)	29.0	33.0	53.3	66.2	69.0
Number of messages	230.4	163.8	15.9	27.2	31.5
Number of sentences	372.6	275.9	24.9	45.8	44.1
Total number of words	1,563.8	1,374.8	224.8	322.9	257.4
Total number of different words	397.5	305.9	118.5	150.5	133.4
Ratio of difficult words to total words	0.3	0.3	0.6	0.5	0.6
Number of words per minute	190.3	171.2	17.3	18.1	10.2

From Interactive human communication by A. Chapanis.

11.325 Presentation of Numeric Data in Person-Computer Dialogue

Key Terms

Data displays; numeric codes; numeric displays; person-computer dialogue

General Description

Well designed formatting of numerical information displays can facilitate the comprehension and comparison of the data by the user. Table 1 presents guidelines for presentation of numeric data.

Applications

Display of numeric information such as part numbers, telephone numbers, scores on a series of tests, and storage dumps; data entry.

Constraints

- Most of these guidelines are not based on experimental studies; others are loosely based on empirical findings.

Key References

1. Brown, C. M., Burkleo, H. V., Mangelsdorf, J. E., Olsen, R. A., & Williams, A. R., Jr. (1981). *Human factors engineering criteria for information processing systems*. Sunnyvale, CA: Lockheed.

2. Engel, S. E., & Granda, R. E. (1975). *Guidelines for man/display interfaces* (TR 00.2720). Poughkeepsie, NY: IBM.

3. Galitz, W. O. (1981). *Handbook of screen format design*. Wellesley, MA: Q. E. D. Information Sciences.

4. Martin, J. (1973). *Design of man-computer dialogues*. Englewood Cliffs, NJ: Prentice-Hall.

5. Parrish, R. N., Gates, J. L., & Munger, S. J. (1981). *Design guidelines and criteria for user/operator transactions with battlefield automated systems. Vol. IV. Provisional guidelines and criteria* (ARI-TR-537-Vol-4). Alexandria, VA: Army Research Institute. (DTIC No. ADA115892)

6. Pew, R. W., & Rollins, A. M. (1975). *Dialog specification procedures* (rev. ed.) (Rep. No. 3129). Cambridge, MA: Bolt, Beranek, & Newman.

7. Smith, S. L. (1981). *Man-machine interface (MMI) requirements definition and design guidelines*. (ESD-TR-81113). Bedford, MA: The MITRE Corp. (DTIC No. ADA096705)

*8. Williges, B. H., & Williges, R. C. (1984). Dialogue design considerations for interactive systems. In F. A. Muckler (Ed.), *Human factors review: 1984*. Santa Monica, CA: Human Factors Society.

Cross References

7.112 Probability of correctly activating discrete controls while reading a meter or other dynamic display;

8.101 Perceiving visual language;

11.326 Presentation of text data in person-computer dialogue;

11.327 Presentation of tabular data in person-computer display;

11.329 Information portrayal in person-computer dialogue

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Table 1. Guidelines for display of numeric data.

Long Numeric Sequences

Should be displayed in groups of three to four when no natural split or pre-defined break occurs (Refs. 1, 2):

Not:	But:
106619751492	1066 1975 1492
121519411861	1215 1941 1861
191418651945	1914 1865 1945
1917	1917

Numeric Fields

1. Lists of numbers without decimals should be right-justified (Refs. 1, 4, 5).
2. Lists of numbers with decimals should use decimal alignment (Ref. 1).
3. Do not assume that the user can identify individual fields because of past familiarity; context plays a significant role. Therefore, identify or label the field (Ref. 2).
4. Present data fields in some recognizable order for ease of scanning and identification. For example, put historical dates in chronological order (Ref. 2).
5. Numeric codes should be restricted to six or fewer digits (Ref. 3).
6. Leading zeros should not be required except where needed for clarity (Refs. 1, 2, 3, 7).

Standard Formats

1. Identical data should be presented to the user in a standard and consistent manner, despite its module of origin (Ref. 2).
2. Do not change current accepted formats, except when a task or activity must be clearly differentiated from other similar tasks (Ref. 2).
3. Suggested standardization of basic data fields for American civilian users (Ref. 2):

   Telephone: 914-444-0111
   Time: HH:MM:SS, HH:MM, MM:SS(.S)
   Date: MM/DD/YY

11.326 Presentation of Text Data in Person-Computer Dialogue

Key Terms

Alphanumeric coding; information portrayal; interactive systems; person-computer dialogue; text display

General Description

A good format for text-based information can facilitate comprehension and comparison of the data by the user. Table 1 present guidelines for presentation of text data.

Constraints

- Most of these guidelines are not based on experimental studies; others are loosely based on empirical findings.

Key References

1. Brown, C. M., Burkleo, H. V., Mangelsdorf, J. E., Olsen, R. A., & Wiliams, A. R., Jr. (1981). *Human factors engineering criteria for information processing systems*. Sunnyvale, CA: Lockhead.

2. Engel, S. E., & Granda, R. E. (1975). *Guidelines for man/display interfaces* (TR 00.2720). Poughkeepsie, NY: IBM.

3. Galitz, W. O. (1981). *Handbook of screen format design*. Wellesley, MA: Q. E. D. Information Sciences.

4. Martin, J. (1973). *Design of man-computer dialogues*. Englewood Cliffs, NJ: Prentice-Hall.

5. Parrish, R. N., Gates, J. L., & Munger, S. J. (1981). *Design guidelines and criteria for user/operator transactions with battlefield automated systems. Vol. IV: Provisional guidelines and criteria* (ARI-TR-537-VOL-4). Alexandria, VA: U.S. Army Research Institute. (DTIC No. ADA115892)

*6. Williges, B. H., & Williges, R. C. (1984). Design considerations for interactive computer systems. In F. A. Muckler (Ed.), *Human factors review: 1984*. Santa Monica, CA: Human Factors Society.

Cross References

8.113 Eye movements during reading: effect of "local" text characteristics;

8.128 Schema theory of memory for text;

8.129 Measurement of text readability;

11.325 Presentation of numeric data in person-computer dialogue;

11.327 Presentation of tabular data in person-computer display;

11.329 Information portrayal in person-computer dialogue;

11.330 Abbreviations and acronyms in person-computer dialogue

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Considerations for display of text data.

Display of Text Data

1. Small screen—use no more than 50-55 characters per line of data (Refs. 2, 3)
2. Large screen—use two or more columns of 30-35 characters per line (Refs. 2, 3)
3. Mixture of upper- and lower-case is preferable (Refs. 1, 2, 3)
4. Left-justify text (Refs. 1, 2, 4, 5)
5. Separate paragraphs by at least one blank line (Ref. 2)
6. For reading ease, field width should be 40 characters or less (Ref. 3)

Display of Alphanumeric Data

1. Character types should be grouped rather than interspersed (Refs. 2, 6)
2. Strings of five or more alphanumerics should be grouped at natural breaks or should be grouped into three of four characters when no natural split or predefined break occurs (Ref. 4)

Multi-Column Displays

1. Right-justify text—separate columns by at least eight spaces (Refs. 2, 3)
2. Left-justify text—separate columns by three to four spaces (Refs. 2, 3)

Grammatical Style

1. Statements should be made in the affirmative (Refs. 1, 3)
2. Active voice should be used whenever possible (active voice is generally easier to understand than passive voice) (Ref. 1)
3. If a sentence describes a sequence of events, the word order in the sentence should correspond to the temporal sequence of events (Refs. 1, 3)
4. Short simple sentences should be used (Refs. 1, 3)
5. Sentences should begin with the main topic (Refs. 1, 3)

11.327 Presentation of Tabular Data in Person-Computer Display

Key Terms

Data tables; information portrayal; person-computer dialogue; tabular data

General Description

Display of data in tabular format facilitates comprehension and comparison of the data. Table 1 presents guidelines for formatting data into tables.

Constraints

- Most of these guidelines are not based on experimental studies; others are loosely based on empirical findings.
- Abstracted tabular displays should offer, as an option, the ability to look at the raw data (Ref. 3)

Key References

1. Brown, C. M., Burkleo, N. V., Mangelsdorf, J. E., Olsen, R. A., & Williams, A. R., Jr. (1981). *Human factors engineering criteria for information processing systems*. Sunnyvale, CA: Lockheed.

2. Cropper, A. G., & Evans, S. J. W. (1968). Ergonomics and computer display design. *The Computer Bulletin, 12*, 94-98.

3. Engel, S. E., & Granda, R. E. (1975, December). *Guidelines for man/display interfaces* (Tech. Rep. No. 00.2720). Poughkeepsie, NY: IBM.

4. Smith, S. L. (1981, February). *Man-machine interface (MMI) requirements definition and design guidelines*. (ESD TR-81-113). Bedford, MA: MITRE Corp. (DTIC No. ADA096705)

*5. Williges, B. H., & Williges, R. C. (1984). Dialogue design considerations for interactive computer systems. In F. A. Muckler (Ed.), *Human factors review: 1984*. Santa Monica, CA: Human Factors Society.

Table 1. Guidelines for display of tabular data.

Formatting Data into Lists

1. Start each item on a new line (Ref. 1)
2. Arrange items in a recognizable and useful order (Ref. 1), such as:

   Alphabetical
   Chronological
   Frequency of use
   Functional
   Importance
   Sequential

3. Items not used for selection may be enumerated with "bullets" (Ref. 1)
4. Block tabular data displays, whenever possible, to reduce user search time for data (Ref. 2)
5. When a list extends beyond the amount that can be shown on one display page, a short message should be provided to indicate that the list is not complete (Ref. 1)

Justification of Lists

1. For rapid scanning, lists should be left-justified and aligned vertically. Subclasses can be indented (Ref. 3)
2. The computer should handle the left- or right-justification of data entries and the justification of numeric lists on the decimal point (Ref. 4)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Cross References

11.325 Presentation of numeric data in person-computer dialogue;

11.326 Presentation of text data in person-computer dialogue;

11.329 Information portrayal in person-computer dialogue

11.328 Graphics in Person-Computer Display

Key Terms

Animation; computer graphics; data graphs; information portrayal; person-computer dialogue; spatial visualization

General Description

Graphic presentations greatly aid interpretation and comparisons of numeric or spatially oriented data. In Table 1, guidelines are given for design of graphic displays.

Applications

Spatial visualization problems; problems with multiple interacting dimensions; display of numeric data; graphic dialogues.

Constraints

- Although data in graphic form are more easily inspected and compared, raw data should be provided as a user option (Ref. 2).
- Most of these guidelines are not based on experimental studies; others are loosely based on empirical findings.

Key References

1. Barmack, J. E., & Sinaiko, H. W. (1966). *Human factors problems in computer-generated graphic displays* (Study S- 234). Washington, DC: Institute for Defense Analyses.

2. Engel, S. E., & Granda, R. E. (1975). Guidelines for man/display interfaces (TR 00.2720). Poughkeepsie, NY: IBM.

3. Foley, J. D., Wallace, V. L., & Chan, P. (1981, January). *The human factors of graphic interaction: Tasks and techniques* (GWU-12ND-81-3). Washington, DC: George Washington University.

4. Martin, J. (1973). *Design of man-computer dialogues*. Englewood Cliffs, NJ: Prentice-Hall.

5. Newman, W. M., & Sproull, R. F. (1979). *Principles of interactive computer graphics*. New York: McGraw-Hill.

6. Schultz, H. G. (1961). An evaluation of methods for presentation of graphic multiple trends: Experiment III. *Human Factors, 3,* 108-119.

*7. Williges, B. H., & Williges, R. C. (1984). Dialogue design considerations for interactive computer systems. In F. A. Muckler (Ed.), *Human factors review: 1984*. Santa Monica, CA: Human Factors Society.

Cross References

8.106 Visual language processing of words and pictures;

11.219 Canonical and non-canonical views: from layout to eye;

11.317 Data entry displays;

11.329 Information portrayal in person-computer dialogue;

11.332 Screen layout and structuring in person-computer displays

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Design guidelines for graphic presentations.

Labels

1. Describe what is being displayed rather than just naming display (Ref. 1)
2. Always label graph axes (Ref. 4)

Axis Subdivision and Scales

1. Letter size used for labeling scales should be independent of scales. If display is contracted to a smaller size, labels must remain large enough to be readable (Ref. 1)
2. Units of 1, 2, 5, or 10 should be used to subdivide scales, not 3, 7, or numbers arbitrarily obtained through division (Ref. 1)
3. Limit number of graduation marks to nine (Ref. 1)
4. Number scales, starting at zero (Ref. 1)
5. Increase magnitude clockwise (left to right; bottom to top)

Displayed Values

1. Maximize contrast between values and scale markings (Ref. 1)
2. Multiple trend lines on single graph facilitate comparison (Ref. 6)

Symbols

Consider the graphics conventions familiar to users (Ref. 5)

Display Complexity

Avoid unnecessary ornamentation, unwanted graphic patterns and illusions, and alignment flaws (Ref. 5)

Display Rotation

1. Center of rotation should be center of object
2. Labels should not rotate with object if they will not remain horizontal

11.329 Information Portrayal in Person-Computer Dialogue

Key Terms

Alphanumeric coding; blink coding; brightness coding; color coding; highlighting; information portrayal; person-computer dialogue; shape coding

General Description

Coding of displayed information can increase the efficacy of interpretation by emphasizing relationships between displayed data elements and by reducing a user's search-and-identification time. Table 1 describes five principal information coding techniques and indicates critical factors for selection of optimal codes. Techniques are presented in approximate order of effectiveness, with color coding the preferred method.

Table 1. General guidelines for selection of information coding techniques.

Code Type	Recommended Applications	Limitations	Design Guidelines
Color	Search Tasks Highlighting of related data in a display Locating: 1. Headings 2. Out-of-tolerance data 3. Newly entered data 4. Important data fields 5. Urgent data	Color blindness (especially red-green) in 8% of males Three to ten hue (color) limit Maximum of eleven codes should be used Registration of overlaid colors Warm colors (red, yellow) generally appear larger than cool colors (blue, green) in graphics Color codes may not transfer required information to monochromatic displays	Consider established color meanings in code selection, example: 1. Red = Danger 2. Yellow = Caution 3. Green = Normal Color codes should be unique and defined on display Recommended colors (Ref. 1): 1. Green = principal color 2. White = headings 3. Pink = alarms 4. Yellow = related data 5. Turquoise/Cyan = user input
Shape 1. Geometric 2. Pictographs	Search and identification tasks	Maximum of 15 shapes	Use of fewer shapes increases accuracy of identification
Blinking	Alarms Target detection tasks in high density displays	Not for use with long-phosphor displays Maximum of four different blink rates	User-optional is preferable Blinking should cease after user response Blink rate should match user's reading scan rate Binary coding is preferred Recommended blink rates: 1. 2-3 Hz with 80 msec minimum (Ref. 2) 2. 3-7 Hz (Ref. 7)
Brightness	User-selected display items	10% or less of display should be highlighted at once No more than three levels of brightness	Provide maximum contrast between highlighted items and other items
Alphanumeric	Absolute identifications	Confusion of symbols	Avoid use of frequently confused character pairs, including: 1. S-5 2. I-1 3. O-0 4. Z-2

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Applications

Qualitative information displays; quantitative information displays.

Constraints

- Codes must be meaningful and consistent with user expectations and population stereotypes.
- Coding for attention-getting should not be overused, or effectiveness will diminish.
- Coding that will reduce legibility or increase transmission time should not be used.
- Color coding can be seriously degraded if ambient illumination is not controlled.
- Coding typically should be redundant.

Key References

1. Brown, C. M., Burkleo, H. V., Mangelsdorf, J. E., Olsen, R. A., & Williams, A. R., Jr. (1981, June). *Human factors engineering criteria for information processing systems*. Sunnyvale, CA: Lockheed.

*2. Engel, S. E., & Granda, R. E. (1975). *Guidelines for man/display interfaces* (00.2720). Poughkeepsie, NY: IBM.

3. Galitz, W. O. (1981). *Handbook of screen format design*. Wellesley, MA: Q. E. D. Information Sciences.

4. Hutchinson, R. D. (1981). *New horizons for human factors in design*. New York: McGraw-Hill.

5. Miller, L. A., & Thomas, J. C., Jr. (1976, December). *Behavioral issues in the use of interactive systems* (RC6326). Yorktown Heights, NY: IBM.

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*7. Ramsey, H. R., & Atwood, M. E. (1979). *Human factors in computer systems: A review of the literature* (SAI-79- 111-DEN). Englewood, CO: Science Applications, Inc. (DTIC No. ADA075679)

*8. Williges, B. H., & Williges, R. C. (1984). Dialogue design considerations for interactive computer systems. In F. A. Muckler (Ed.) *Human factors review: 1984*. Santa Monica, CA: Human Factors Society.

Cross References

8.106 Visual language processing of words and pictures;

11.202 Redundant coding: use of color in conjunction with other codes;

11.325 Presentation of numeric data in person-computer dialogue;

11.326 Presentation of text data in person-computer dialogue;

11.327 Presentation of tabular data in person-computer display;

11.328 Graphics in person-computer display

11.330 Abbreviations and Acronyms in Person-Computer Dialogue

Key Terms

Alphanumeric coding; command language; dialogue design; mnemonics; person-computer dialogue; truncation

General Description

Terse and unambiguous abbreviations or acronyms, when used for input tasks, can increase user satisfaction and productivity by reducing keying time, lowering input error frequency, and reducing user involvement in error recovery procedures. For output displays, abbreviations reduce reading time and convey information in less physical display space. Unless thoughtfully designed, however, abbreviations (even simple truncation) can become confusing to the user and negate the potential performance benefits. Table 1 presents guidelines for successful design of abbreviations.

Applications

Command language design; alphanumeric displays; text data entry.

Constraints

- Words that are short (4 letters or less) should not be abbreviated unless a standard abbreviation exists (e.g., V for volt).
- Critical actions should not be made dependent upon a single key-stroke response (e.g., Y for yes or N for no).
- Abbreviations are not suggested for displays (in general).

Key References

1. Brown, C. M., Burkleo, H. V., Mangelsdorf, J. E., Olsen, R. A., & Williams, A. R., Jr. (1981). *Human factors engineering criteria for information processing systems.* Sunnyvale, CA: Lockheed.

2. Ehrenreich, S. L. (1981). Query languages: Design recommendations derived from the human factors literature. *Human Factors, 23,* 709-725.

3. Galitz, W. O. (1981). *Handbook of screen format design.* Wellesley, MA: Q. E. D. Information Sciences.

4. Moses, F. L., & Ehrenreich, S. L. (1981). Abbreviations for automated systems. *Proceedings of the Human Factors Society 25th Annual Meeting* (pp. 132-135). Santa Monica, CA: The Human Factors Society.

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*7. Ramsey, H. R., & Atwood, M. E. (1979). *Human factors in computer systems: A review of the literature* (Tech. Rep. No. SAI-79-111-DEN). Englewood, CO: Science of Applications Inc. (DTIC No. ADA075679)

8. Smith, S. L. (1981). *Man-machine interface (MMI) requirements definition and design guidelines.* (ESD-TR-81-113). Bedford, MA: The MITRE Corp. (DTIC No. ADA096705)

9. Smith, S. L., & Aucella, A. F. (1983). *Design guidelines for the user interface to computer-based information systems* (ESD-TR-83-122). Bedford, MA: The MITRE Corp. (DTIC No. ADA127345)

10. Williges, B. H., & Williges, R. C. (1983). Dialogue design considerations for interactive computer systems. In F. A. Muckler (Ed.), *Human factors review: 1984.* Santa Monica, CA: Human Factors Society.

Cross References

11.326 Presentation of text data in person-computer dialogue;

11.327 Presentation of tabular data in person-computer display;

11.329 Information portrayal in person-computer dialogue;

11.331 Prompting in person-computer dialogue;

11.333 Guidelines for multiple-frame person-computer display design;

11.334 Design guidelines for multiple-level person-computer displays

Table 1. Guidelines for design of abbreviations and acronyms.

General Guidelines

1. Provide option for use of abbreviations or full command (Refs. 1, 5)
2. Instruct user as to method used for selecting command abbreviations (Ref. 2)
3. Definition of data-entry codes or abbreviations by the user should be allowed (Ref. 5)
4. Contractions should not be used on electronic displays (Refs. 1, 4)

Abbreviation Design

Abbreviations should be:

1. Limited to one per word (Ref. 1)
2. Considerably shorter than the original term (Refs. 1, 2)
3. Mnemonically meaningful (Refs. 1, 2, 4)
4. Distinctive to avoid confusion (Refs. 1, 3)
5. Composed of unrestricted alphabetic sets when alphabetic data-entry is required (Ref. 8)
6. Consistent with unabbreviated command input (Refs. 1, 7)
7. Simple truncation when used with command names (Ref. 2)

Expansion of Abbreviations

Abbreviations should be permitted in text entry and expanded later by the computer (Ref. 1)

11.331 Prompting in Person-Computer Dialogue

Table 1. Input format and recommended prompt forms.

Input Format	Prompt Form
General Purpose	Commentary on Screen
General Purpose	Selectively Illuminating Function Keys
Positional Data	Tracking Cross
Text String	Blinking Cursor
Numerical Data	Quantitative Scale/Dial

Key Terms

Command language; cursor control; person-computer dialogue; prompting

General Description

Prompting, regardless of form, provides a cue for required user inputs in person-computer dialogue. The effectiveness of prompting can be enhanced by designing the prompts to be clear and understandable, emphasized by highlighting, uniqueness, and consistent location. Table 1 provides recommended prompt forms for various input formats.

Applications

System-initiated requests for information to be input by user; structuring of command language when used by inexperienced users.

Constraints

- Prompting form should be selected as a function of desired input-type.

Key References

*1. Engel, S. E., & Granda, R. E. (1975). *Guidelines for man/display interfaces* (Rep. No. 00.2720). Poughkeepsie, NY: IBM.

2. Foley, J. D., & Wallace, V. L. (1974). The art of graphic man-machine conversation. *Proceedings of the IEEE*, 62, 462-471.

*3. Williges, B. H., & Williges, R. C. (1984). Dialogue design considerations for interactive computer systems. In F. A. Muckler (Ed.), *Human factors review: 1984*. Santa Monica, CA: The Human Factors Society.

Cross References

11.321 Design and control of cursors;

11.332 Screen layout and structuring in person-computer displays;

12.422 Comparison of cursor control devices

Notes

11.332 Screen Layout and Structuring in Person-Computer Displays

Table 1. Guidelines for screen layout and structuring. (From Ref. 11)

Windowing and Partitioning of Display

1. The display should not be divided into many small windows (Refs. 2, 3).
2. The user should be permitted to divide the screen into windows or functional areas of an appropriate size for the task (Ref. 6).
3. Dashed lines may be used to segment the display (Ref. 4).
4. The unused areas should be used to separate logical groups, rather than having all the unused area on one side of the display (Ref. 1).
5. In data entry and retrieval tasks, the screen should be functionally partitioned into different areas to discriminate among different classes of information for commands, status messages, and input fields (Refs. 3, 5).
6. To enhance important or infrequent messages and alarms, they should be placed in the central field of vision relative to the display window (Refs. 2, 10).

Organization of Fields

1. The organization of displayed fields should be standardized. Functional areas should remain in the same relative location on all frames. This permits the users to develop spatial expectancies. For example, functional areas reserved for a particular kind of data should remain in the same relative display location throughout the dialogue (Refs. 1, 2, 3, 7).
2. For data-entry dialogues, an obvious starting point in the upper-left corner of the screen should be provided (Ref. 3).
3. To avoid clutter, data should be presented using spacing, grouping, and columns to produce an orderly and legible display (Refs. 1, 3).
4. Data should be arranged in logical groups: sequentially, functionally, by importance, or by frequency (Ref. 1).
5. Logically related data should be clearly grouped and separated from other categories of data. On large, uncluttered screens, the display or functional areas should be separated by blank spaces (3-5 rows and/or columns). On smaller and/or more cluttered screens, structure can be defined by other coding techniques, such as using different surrounding line types, line widths, intensity levels, geometric shapes, color, etc. (Refs. 2, 3, 10).
6. Data should be arranged on the screen so that the observation of similarities, differences, trends, and relationships is facilitated for the most common uses (Ref. 1).

Instructions and Supplemental Information

1. In computer-initiated dialogues, each display page should have a title that indicates the purpose of the page (Ref. 8).
2. Instructions should stand out. For example, instructions may be preceded by a row of asterisks (Refs. 1, 4).
3. Instructions on how to use a data-entry screen should precede the screen or appear at the top of the screen (Ref. 3).
4. Instructions concerning how to process a completed data-entry screen should appear at the bottom of the screen (Ref. 3).
5. Symmetrical balance should be maintained by centering titles and graphics (Ref. 3).
6. In data entry and retrieval tasks, the last four lines on each display page should be reserved for messages, to indicate errors, communication links, or system status (Ref. 8).
7. When command language is used for control input, an appropriate entry area should be provided in a consistent location on every display, preferably at the bottom of the screen if the cursor can be conveniently moved there (Ref. 9).
8. Displays should be designed so that information relevant to sequence control should be distinctive in position and/or format (Ref. 9).
9. Frequently appearing commands should appear in the same area of the display at all times (Ref. 2).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms

Data entry; information portrayal; screen layout; small screen displays; windowing

General Description

Structuring screen layout allows the presentation of information in ways that make it easier for users to assimilate and that correspond to the limits of human perception and memory. Display of too much information at one time can cause confusion and tax the user's memory. The resulting user reactions include frustration, a high frequency of errors, and (perhaps) eventual refusal to use the system.

Two types of display structuring should be considered: perceptual organization of data displays and sequential and/or hierarchical organization. Table 1 provides a series of guidelines focusing on functional grouping and display consistency concepts that provide increased user awareness of the perceptual organization. Criteria for functional grouping can range from arbitrary but consistent organization to design based on frequency of usage or optimal logic flow. Details for individual **frame** design are provided in the cross references listing according to data type.

Applications

Format of information displays, small screen displays (<4000 characters).

Constraints

- Guidelines may not be based on empirically validated research.
- Only required information should be displayed to avoid information overload or display clutter. Additional information should be available on user request.

Key References

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6. Newman, W. M., & Sproull, R. F. (1979). *Principles of interactive computer graphics*. New York: McGraw-Hill.

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Cross References

11.317 Data entry displays;

11.321 Design and control of cursors;

11.325 Presentation of numeric data in person-computer dialogue;

11.326 Presentation of text data in person-computer dialogue;

11.327 Presentation of tabular data in person-computer display;

11.328 Graphics in person-computer display;

11.329 Information portrayal in person-computer dialogue;

11.330 Abbreviations and acronyms in person-computer dialogue;

11.331 Prompting in person-computer dialogue;

11.333 Guidelines for multiple-frame person-computer display design;

11.334 Design guidelines for multiple-level person-computer display;

11.335 Windowing versus scrolling on visual display terminals

11.333 Guidelines for Multiple-Frame Person-Computer Display Design

Key Terms

Branching dialogue; display format; hierarchical structures; multi-frame displays; sequence control

General Description

The guidelines were synthesized from known human factors/psychological principles, experimental studies, customer/user comments, and informal studies. Table 1 lists guidelines for display of multiple frames in series to minimize dependence on user's memory.

Constraints

- Guidelines are not standards: Designers should consider modifications required by specific system/application needs.
- Guidelines cannot provide quantification without empirical study.
- Systematic studies of interface design may provide more detailed/updated guidelines.
- Multiple-frame display design must also consider single-frame display guidelines.
- Pilot testing is desirable to validate guidelines in application usage.

Table 1. Guidelines for multiple-level displays.

- Provide present and maximum locations on viewed portion when scrolling a large logical **frame**. Example: "Line 72 of 117"
- Provide user control of amount, format, and complexity of displayed system information
- Display prose text in upper and lower case. Labels, titles or attention-getting message, use upper case only

Not:	But:
ALL UPPER CASE TEXT IS HARDER TO READ THAN A MIXTURE OF UPPER AND LOWER CASE	Normal reading is easier if the text is in both upper and lower case

- Minimize user's need to remember data from frame to frame; provide visible audit trail of choices

First Frame	Second Frame	Third Frame
Pick one:	GPSS	GPSS—TRANSFER
FORTRAN	Pick one:	Pick one:
PL/I	ADVANCE	Fractional
GPSS	TRANSFER	Pick
...	UNLINK	Unconditional
		...

- Use consistent meanings and context of technical words. Consider user's viewpoint, not programmer's
- Keep lists small (four to six items) to increase comprehension
- Standardize spatial position of appearing/disappearing screen items:
  a. Commands in same location on screen
  b. Show items in same location in list regardless of number of items
- Maintain system control of essential data, text, formats, etc., rather than user control

Key References

*1. Engel, S. E., & Granda, R. E. (1975). *Guidelines for man/display interfaces* (TR00.2720). Poughkeepsie, NY: IBM Poughkeepsie Laboratory.

Cross References

11.334 Design guidelines for multiple-level person-computer displays

11.334 Design Guidelines for Multiple-Level Person-Computer Display

Table 1. Checklist for multiple-level display considerations. (Adapted from Ref. 1)

Display Levels	Yes	Not Applicable	Not Known	No
If the system has multiple display levels, does the system:				
a. Minimize the number of levels required?	____	____	____	____
b. Provide priority access to the more critical display levels?	____	____	____	____
c. Provide the user with information about the current position within the sequence of levels?	____	____	____	____
d. Ensure similarity, wherever possible, between display formats at each level?	____	____	____	____
e. Supply all data relevant to making an entry on one display **frame**?	____	____	____	____

Key Terms

Branching dialogue; hierarchical dialogue; menu dialogue; multi-frame displays

General Description

Displays with multiple levels that the users must negotiate to accomplish a task must provide mechanisms for accuracy and ease of use. Table 1 provides a checklist of critical design considerations.

Applications

Interactive dialogue requiring use of multiple dialogue levels; hierarchical or branching dialogue; computer-initiated questioning, form-filling or menu-selection dialogue.

Constraints

- Guidelines are not standards: Designers should consider modifications required by specific system/application needs.
- Guidelines cannot provide quantification without empirical study.
- Multiple-frame display design must also consider single-frame display guidelines.
- Pilot testing is desirable to validate guidelines for specific applications.

Key Terms

1. Henricks, D., Kilduff, P., Brooks, P., Marchak, B., & Doyle, B. (1982). *Human engineering guidelines for management information systems* (DOD-HDBK-761). Alexandria, VA: U.S. Army Material Development and Readiness Command.

Cross References

11.333 Guidelines for multiple-frame person-computer display design

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Notes

11.335 Windowing Versus Scrolling on Visual Display Terminals

Table 1. Major findings of research comparing windowing and scrolling.

Consistent user performance is facilitated by restricted views, rather than unrestricted views, of system information.

When allowed to choose system modes, more novice users chose window mode.

Window displays are more efficient than scrolling displays: users performed tasks more quickly with fewer moves and with less error.

Explanation and demonstration of display modes do not affect performance.

The use of keytop scroll figures  as opposed to arrows → does not improve performance

Key Terms

Display format; hierarchical data displays; information portrayal; scrolling; sequence control; windowing

General Description

Two conceptualizations of data displays are common when available data exceed the display capability of a video display terminal (VDT): (1) windowing and (2) scrolling. The windowing concept allows selection of views of "stationary" data, whereas scrolling provides a movement of the data observable through a "stationary" VDT.

"Intuitive" advantages of each concept have resulted in the adoption of both types of data displays in various systems. Empirical research indicates a population stereotype in favor of, and a superiority of, windowing. Conclusive findings in applied problem-solving tasks, however, are pending. Windowing is believed to provide a more optimal outline of the overall structure, thus reducing the memory load on the user. Table 1 describes the major finding of windowing versus scrolling.

Methods

Test Conditions

Study 1 (Ref. 2)

- Display of number vector (horizontal) and letter vector (vertical) intersecting at "12-13" and "L-M"; vectors ended at 7, 18, G, and R in initial position
- Five display conditions (window with training about window concept, window without training, scroll with training, scroll without training, subject-defined mode without training)
- Subjects required to display D, T, 5, or 20

Study 2 (Ref. 1)

- Logic network of six rows and nine columns of units (and gates), with left-to-right flow specified between units (not all positions were filled)
- Fault-finding task required testing individual units by typing in unit number
- For windowing, network divided into nine pages of two rows and three columns; observer could access top-level display showing flow between pages or individual pages showing flow between units; initial position was top-level display
- For scrolling, display was same size as a page for windowing and could move either vertically or horizontally; initial position was top right-hand corner of network

Experimental Procedure

Study 1

- Between-subjects design
- Independent variable: display condition
- Dependent variables: time for problem solution, number of moves
- Observer's task: move display to display requested data (example: show "x" and "20")
- 188 high school students

Study 2

- Between-subjects design
- Independent variables: types of display (windowing, scrolling), performance during practice
- Dependent variables: solution time, efficiency
- Observer's task: test individual units and diagnose fault
- 23 high school and undergraduate college students

Experimental Results

Study 1

- A significantly greater number of novice users choose windowing mode (79%) ($p < 0.05$).
- Groups using windows perform significantly faster and with fewer number of moves overall ($p < 0.05$).
- Explanation and description of the appropriate concept do not have a significant effect on performance.
- Type of keytop marking does not have a significant effect on performance (determined in separate experiment).

Study 2

- Windowing format improves the efficiency of the fault diagnosis task rather than ensuring correct problem solution.
- Restricting the proportion of information displayed substantially restricts between-subject variance in the fault-finding measures.
- The poor performers during practice did much worse with the scrolling displays; there was relatively little difference among the other three groups (but significance was not tested among groups).

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Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Variability

There was very high between-subject variance in Study 2.

Repeatability/Comparison with Other Studies

Results for two studies are reported.

Constraints

- Applicability of these findings to experienced users of computers or specific systems is unknown.

Key References

*1. Brooke, J. B., & Duncan, K. D. (1983). A comparison of hierarchically paged and scrolling displays for fault-finding. *Ergonomics, 26*, 465-477.

*2. Bury, K. F., Boyle, J. M., Evey, R. J., & Neal, A. S. (1982). Windowing versus scrolling on a visual display terminal. *Human Factors, 24*, 385-394.

Cross References

7.117 Probability of failure to detect in periodic scanning of displays;

11.114 Display element size: effect on reading and search times;

11.319 Sequence control in person-computer dialogue;

11.321 Design and control of cursors

11.336 Guidelines for the Use of Noncritical Auditory Signals

Table 1. Guidelines for design of auditory signals. (Adapted from Ref. 1)

1. The auditory signal should be used to alert and direct the user's attention to the appropriate visual display
2. The optimum type of signal should be carefully evaluated, so that it is readily noticed by the user while not startling or interfering with others in the immediate area. Because of variable background noises, the intensity should be adjustable
3. The intensity, duration, and source location of the signal should be compatible with the acoustical environment of the intended receiver as well as with the requirements of other personnel in the signal area
4. Auditory signals should be intermittent, allowing the user sufficient time to respond. The signal should be automatically shut off by user response action
5. Auditory signals should be triggered by system failures
6. Non-critical auditory signals should be capable of being turned off at the discretion of the user

Key Terms

Alerting systems; attentional directors; auditory warnings; bells

General Description

Auditory signals can be used to supplement interactive visual displays in critical and noncritical situations. They are best, however, for critical situations. Auditory signals should be used in situations where visual task loading on the operator is high, or when visually presented messages may be overlooked or misinterpreted. For example, when system response is >15 sec, an auditory signal can indicate the "system ready" state. This allows the user to use that time productively for other tasks without being required to monitor the visual display. Table 1 lists general guidelines that define desirable characteristics of noncritical auditory signals.

Applications

Attention-getting; announcing changes in system state; declaring system or input/output failure.

Constraints

- Guidelines may not have been empirically validated.

Key References

*1. Hendricks, D., Kilduff, P., Brooks, P., Marshak, R., & Doyle, B. (1982). *Human engineering guidelines for management information systems* (DOD-HDBK-761). Alexandria, VA: U.S. Army Material Development and Readiness Command.

Cross References

5.1015 Speeding of reaction time by intersensory warning signals;

5.1021 Detection of auditory-visual asynchrony;

11.313 System response time and the effect on user performance and satisfaction;

11.413 Coupling of visual and auditory warning signals: effects on detection and recognition;

11.415 Coupling of visual and verbal warning signals: effect on response time;

11.421 Integration of visual and auditory alerts in warning systems

Notes

11.401 Guidelines for Designing Alerting Signals

Table 1. Guidelines for minimizing time for detection of alerts. (From Ref. 1)

1. Present high-priority alerting signals both visually and aurally. Maximize the probability of detection of each mode of the warning signal
2. The detectability of high-priority visual alerting signals should be maximized as follows:
   a. Present visual alerting signals as close to the operator's line of sight as possible. Maximum deviation of 15° for high-priority alerts and 30° for lower priority
   b. Visual alerting signals should subtend at least 1° of visual angle
   c. Visual alerting signals should be twice as bright as other visual displays on the instrument panel
   d. A visual alerting signal should be flashing against a steady-state background
   e. High-priority visual alerting signals should be colored red; cautionary signals, amber; and advisory signals green or blue
   f. Legends on high-priority signals should be opaque with an illuminated background. On lower-priority signals the legend should be illuminated with an opaque background
   g. Legend height should be at least 0.25 inch with a height-to-width ratio of 3.5 and a stroke width of at least 0.125 of the height
   h. If visual signals are to be located in the peripheral visual field, a master signal should be used
   i. False signals should be minimized and a method of canceling the signal should exist
3. The detectability of auditory alerting signals should be maximized as follows:
   a. Auditory alerts should be multiple frequency with more than one frequency in the range of 250 to 4000 Hz
   b. The amplitude of an auditory signal should be at least 15 dB above the amplitude of the masked threshold
   c. An auditory alerting signal should be intermittent or changing over time
   d. Auditory alerting signals should be dichotically separated from auditory distractors and noise. If dichotic separation is not possible, warning signals should come from a location that is separated by at least 90° from the source of interfering noise or signals. In addition, if the locations of both the source of the warning signal and the source of the interfering sounds are optional, the warning signal should be presented to the dominant ear and other sounds should be presented to the non-dominant ear
   e. An attention-intruding signal (e.g., the person's name) should be given at the beginning of an alerting signal
   f. Exposure/time constraint must be followed on all levels of signal priority
4. The use of tactile alerts is not recommended due to the possible disruptive effects of tactile stimuli. However, if tactile alerting signals are used, detectability may be maximized as follows:
   a. Tactile warning signals should be delivered by vibratory apparatus that will always be in contact with the body
   b. The amplitude of the vibration should be detectable by the region of the body that is stimulated
5. Other general guidelines are:
   a. A warning signal should be presented until the operator responds
   b. Distracting stimuli and workload should be minimized while warning signals are being presented

Key Terms

Alerting systems; attention; auditory warnings; cautions; reaction time; signal detection; tactual warnings; voice signals; warnings

General Description

The experimental results reviewed in Ref. 1 were used to form guidelines for minimizing detection times (Table 1) and response times (Table 2) for high-priority signals. Less rigid criteria can be used for low-priority signals. The priority of a signal is based solely on the time an operator has to respond before the point where a response will not change the outcome of the situation.

Constraints

- Other criteria may be used in establishing signal priorities.

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Key References

*1. Boucek, G. P., Jr., Veitengruber, J. E., & Smith, W. D. (1977, May). *Aircraft alerting systems criteria study. Vol. II. Human factors guidelines for aircraft alerting systems* (FAA-RD-76-222-2). Washington, DC: Department of Transportation, Federal Aviation Administration. (DTIC No. ADA043383)

Cross References

11.402 Alarm classification and development

Table 2. Guidelines for minimizing time from detection to effective response. (From Ref. 1)

1. The number of steps in the data collection should be minimized
2. Voice signals should be used along with visual signals
3. The effectiveness of voice signals may be maximized as follows:
   a. The language and phraseology should be familiar to the operator
   b. The message should be preceded by an alerting tone, word, or phrase (CRef. 11.402)
   c. Synthesized voice systems may be used if every effort is made to simplify the communication task
   d. The warning system should have capability of attenuating other voice systems while the warning is activated
4. A warning signal should not be confusable with any other signal

11.402 Alarm Classification and Development

Table 1. Classification of alarms. (From Ref. 4)

Alarm category	Response mode
Warning	Requiring immediate attention and mandatory immediate response
Caution	Requiring immediate attention and rapid response
Advisory	Requiring general awareness of a marginal condition
No-Display/ Information	Conditions which, though potential dangers, are not amenable to display because of absence of adequate sensors: e.g., major structural failure

Key Terms

Alerting systems; cautions; event criticality; safety; warnings

General Description

A first step in designing a warning system is to categorize all the potential failures or system malfunctions in terms of their importance, which is determined by the impact of the malfunction on personnel safety, system hardware safety, or the achievement of mission/task objectives. The more critical the failure, the greater the demand for the alerting and rapid response of the operator. Alarms may be categorized with a corresponding indication of how quickly the alarm should capture attention and the required response (Table 1). Consideration of the following factors can help classify alarms:

- What are the consequences of the event for the operator and for the machine?
- How rapidly will those consequences occur?
- What is the worst that could happen if the alarm is ignored?
- How long will it take to correct the problem?
- How fast will the system recover?

Objective means of assigning events to the categories of alarms should be developed, as questionnaires may yield subjective information, with little agreement among subjects (e.g., 66 aircrew members, most of whom were pilots, strongly disagreed among themselves about how to place 22 events into the categories listed in Table 1). Then, based on the findings concerning these factors, appropriate modes of capturing attention should be selected to meet the necessary response times.

In an efficient warning system, a signal must be salient enough to capture the operator's attention without causing a disruptive response that impairs the operator's performance; at the same time, the system should prevent the operator from ignoring the alarm and taking no action (he should at least acknowledge) within a reasonable amount of time. The signal should provide enough information for operator selection of the appropriate response (e.g., type and urgency of problem and possibly guidance and/or assistance in correcting the problem).

Pilots (number not reported) participating in a survey reported in Ref. 6 agree that:

1. There are too many alerts, particularly auditory alerts. Most pilots thought there should be no more than four auditory alerts, and one is preferred.
2. The intensity (loudness) of auditory alerts in current use should be decreased.
3. There should be a prioritization of alerts and each alert should carry information about how critical it is.
4. Non-critical alerts should not occur during periods of high workload (e.g., takeoff): they should be delayed.
5. Checklists should be organized to correspond to the categories of criticality for the alerts.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Objective data are difficult to generate if system design is conceptual (e.g., response time for corrective action). Estimates based on experience and literature are necessary.

Key References

1. Berson, B. L., Po-Chedley, D. A., Boucek, G. P., Hanson, D. C., & Leffler, M. F. (1981, January). *Aircraft alerting systems standardization study. Vol. II. Aircraft alerting system design guidelines* (FAA-RD-81-3812). Seattle, WA: Boeing Commercial Airplane Co. (DTIC No. ADA106732)

2. *Data Item Description. Human Engineering Signal Analysis Report* (UDI-H-21272). (1973, October). Washington, DC: US Government Printing Office.

3. Department of Defense (DoD). (1970). *Military standard. Aircrew station signals* (MIL-STD-411D). Washington, DC: DoD.

*4. Seminara, J. L. (1965, September). How to apply human factors principles in warning system design. *Machine Design, 37*, 106-116.

5. US Air Force. (1980). *AFSC Design Handbook* (DH 1-3). Washington, DC: US Government Printing Office.

*6. Veitengruber, J. E. (1978). Design criteria for aircraft warning, caution, and advisory alerting systems. *Journal of Aircraft, 15*, 574-581.

11.403 Target Coding: Effect on Search Time

Table 1. Proportion of fixations on objects with various characteristics as a function of the advance information given to the subject at the start of a trial. (From Ref. 4)

Advance information	Color					Size (degrees of visual angle)				Shape				
	Bl	Gr	Ye	Or	Pi	2.8	1.9	1.3	0.8	Ci	Sc	Tr	Sq	Cr
Color	0.61	0.56	0.59	0.71	0.60									
Size						0.59	0.29	0.28	0.35					
Shape										0.26	0.24	0.24	0.23	0.29
Color + Size	0.59	0.56	0.67	0.66	0.59	0.52	0.30	0.30	0.30					
Color + Shape	0.64	0.64	0.66	0.59	0.59					0.25	0.26	0.27	0.24	0.28
Size + Shape						0.57	0.30	0.29	0.35	0.27	0.25	0.26	0.24	0.30
Color + Size + Shape	0.54	0.55	0.55	0.62	0.54	0.49	0.31	0.29	0.28	0.26	0.28	0.25	0.26	0.26
Number Only	0.20	0.20	0.20	0.18	0.22	0.25	0.25	0.26	0.24	0.20	0.20	0.20	0.20	0.20

Key Terms

Alerting systems; attention; attentional directors; color coding; display clutter; maps; peripheral vision; search time; shape; size; target detection; training; visual direction; visual fixation

General Description

In searching for a target in a cluttered visual display, we can use advance knowledge about color and, to a limited extent, about size, to direct eye movements to relevant portions of the display. Advance knowledge directly decreases search time.

Applications

Maps, schematic drawings, instrument panels, and other complex visual displays that require visual search will be easier to use when color coding distinguishes among groups of elements that differ from each other in important ways.

Methods

Test Conditions

- 1.22-m^2 displays, rear projected, subtending 39 deg of visual angle
- Each display contained 100 forms; every form had a two-digit number in the center; number is 0.3 deg visual angle in height; forms within a display varied in size (2.8, 1.9, 1.3, or 0.8 deg), color (pink, orange, yellow, green, or blue), and shape (cross, triangle, square, circle, or semicircle)
- Eye fixation measured using corneal reflection method, preventing observer's use of left eye
- Observer initiated trials, unlimited viewing time

Experimental Procedure

- Within-subject design
- Independent variables: nature of advance information about target (size, color, and/or shape; two-digit number of target always given)
- Dependent variables: locus of eye fixation, time to find target
- Observer's task: locate a target in the display, given either target number alone or target number plus one or more target characteristics
- 30 observers, male college undergraduates with normal acuity and color vision

Experimental Results

- About 115,000 fixations (61%) fell on a specific object in the field. When only target number is given, fixations are unrelated to size, shape, or color (Table 1).
- When target color and number are specified, subjects tend to fixate on targets of that color. When size and number are specified, subjects tend to fixate on targets of the specified size only when the target is of the largest size. When shape and number are specified, subjects do not fixate on targets of the specified shape.
- Mean time to find target increases through these manipulations: color and number specified, size and number specified, shape and number specified, number specified.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The utility of advance color information to speed visual search time is well documented (Refs. 2, 3). Comparable data on size and shape are not as available.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- The presence of color may interfere with subject's ability to use size and shape information.
- Shape information can be used under some conditions to enhance visual detection (Ref. 1) and may be useful as an advance cue in these conditions as well.
- The degree of advantage produced by color coding may depend on how similar the colors are to each other (Ref. 2).

Key References

1. Estes, W. K. (1972). Interactions of signal and background variables in visual processing. *Perception & Psychophysics, 12,* 278-286.

2. Green, B. F., & Anderson, L. K. (1956). Color coding in a visual search task. *Journal of Experimental Psychology, 51,* 19-24.

3. Smith, S. L. (1962). Color coding and visual search. *Journal of Experimental Psychology, 64,* 434-440.

*4. Williams, L. G. (1966). The effect of target specification on objects fixated during visual search. *Perception & Psychophysics, 1,* 315-318.

Cross References

1.915 Effects of target characteristics on eye movements and fixation;

7.506 Search time: effects of target conspicuity and fixation eye movements;

7.515 Processing of nontarget items in visual search;

7.520 Controlled and automatic visual search

Table 2. Mean time in seconds to find the target number as a function of the nature of the advance information specifying the form in which the target was placed. (From Ref. 4)

Color	7.6
Color + Size	6.1
Color + Shape	7.1
Color + Size + Shape	6.4
Size	16.4
Size + Shape	15.8
Shape	20.7
Number Only	22.8

11.404 Visual Versus Auditory Warning Signals

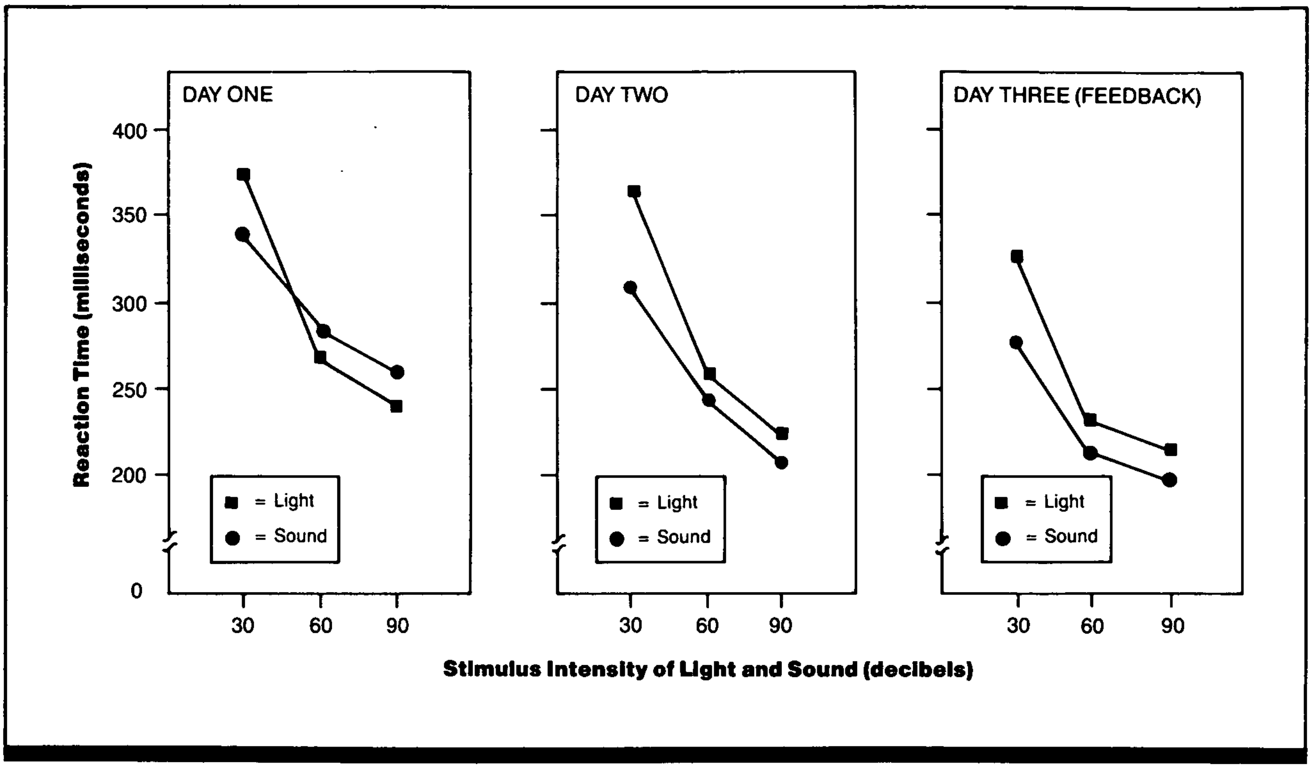


Figure 1. Mean reaction time over three days as a function of stimulus intensity for light and sound (Exp. 1). (From Ref. 3)

Key Terms

Attention intrusion; noise discrimination; reaction time; signal presentation rates; simple reaction time; verbal signals; warnings

General Description

Intense light stimuli in the photopic range of vision are as effective as sounds in initiating fast reactions. At low to moderate sound intensity levels, reaction times (RTs) to auditory stimuli are approximately 20-30 msec faster than RT to visual stimuli. Intensity of sound and white light for photopically adapted observers can be equated by using a decibel scale with a reference of 0.00002 N/m^2 (0.0002 dyne/cm^2) for sound and 3.183×10^{-7} cd/m^2 (10^{-10} L) for light.

Applications

Warning signal design.

Methods

Test Conditions

- Auditory stimuli (generated by audio oscillator) were three 1000-Hz tones of intensities 30, 60, and 90 dB using reference value of 0.00002 N/m^2 (0.0002 dyne/cm^2)
- Visual stimuli were three lights of 3.183×10^{-4}, 0.3183, and 3.183×10^2 cd/m^2 (0.0001, 0.1, and 100 mL, respectively), or 30, 60, and 90 dB with a reference level of 3.183×10^{-7} cd/m^2 (10^{-10} L); white, daylight-color light generated by fluorescent tubes regulated by a shutter and dimming mechanism
- Subject viewed lights through 38.1 × 38.1-cm window of translucent (milky) plexiglass at eye level and ~0.91-m distance
- RT measured in milliseconds by electronic counter; ready signal given by tactile stimulus to left index finger
- Experimental chamber was sound-proof and kept totally dark during the test period; subject was dark adapted for 10 min before each experimental session
- Second experiment with same stimulus conditions, except with 16 intensities of light and sound from 30-60 dB in 2-dB steps

Experimental Procedure

- Independent variables: intensity levels of tones, intensity levels of lights, day of session
- Dependent variable: reaction time, measured from signal onset to depression of key
- Subject's task: depress telegraph key with right index finger in response to stimulus onset; feedback given after each trial on Day 3
- For Exp. 1, 60 male soldiers, 30 in each visual and auditory conditions; for Exp. 2, 2 male and 2 female subjects, one of whom had extensive practice

Experimental Results

- The RT inversely relates to stimulus intensity and the mean RT decreases over days, i.e., with practice, for both stimulus conditions (Fig. 1).
- RTs for high- and middle-intensity visual and auditory signals are similar; magnitude of significant differences in RT between low-intensity visual and auditory signals are greater for Days 2 and 3 than for Day 1 (Fig. 1).
- RT differences between light and sound intensities in the 30-46 dB (low-intensity) range (Fig. 2) are attributable to latency differences in reception at photopic and scotopic levels (i.e., white-light levels that are above the photopic threshold produce RTs similar to those obtained for sound levels in the same range, whereas light levels below the photopic threshold produce RTs that are longer than those for the corresponding sounds).

Variability

Analysis of variance was performed on Exp. 1 data. No statistical analysis was reported for Exp. 2 data.

Repeatability/Comparison with Other Studies

Conclusions concur with previous studies (Refs. 1, 4). Reference 2 reported results that appear to be discrepant, but, on close inspection, they are consistent with Kohfeld's (Ref. 3) conclusions.

Constraints

- Only four subjects participated in Exp. 2, one of which had extensive experience in RT experiments; a larger number of subjects is necessary to reduce individual differences.
- Dominant-hand information was not reported.

Key References

1. Geldard, F. A. (1953). *The human senses*. New York: Wiley.

2. Goldstone, S. (1968). Reaction time to onset and termination of light and sounds. *Perceptual and Motor Skills, 27*, 1023-1029.

*3. Kohfeld, D. (1971). Simple reaction time as a function of stimulus intensity in decibels of light and sound. *Journal of Experimental Psychology, 88*, 251-257.

4. Rease, V. P., & Sticht, T. G. (1965). Reaction time as a function of onset and offset stimulation of the fovea and periphery. *Perceptual and Motor Skills, 20*, 549-554.

Cross References

9.109 Simple reaction time to visual targets;

11.413 Coupling of visual and auditory warning signals: effects on detection and recognition;

11.414 Coupling of master indicators with peripherally located warning displays;

11.421 Integration of visual and auditory alerts in warning systems

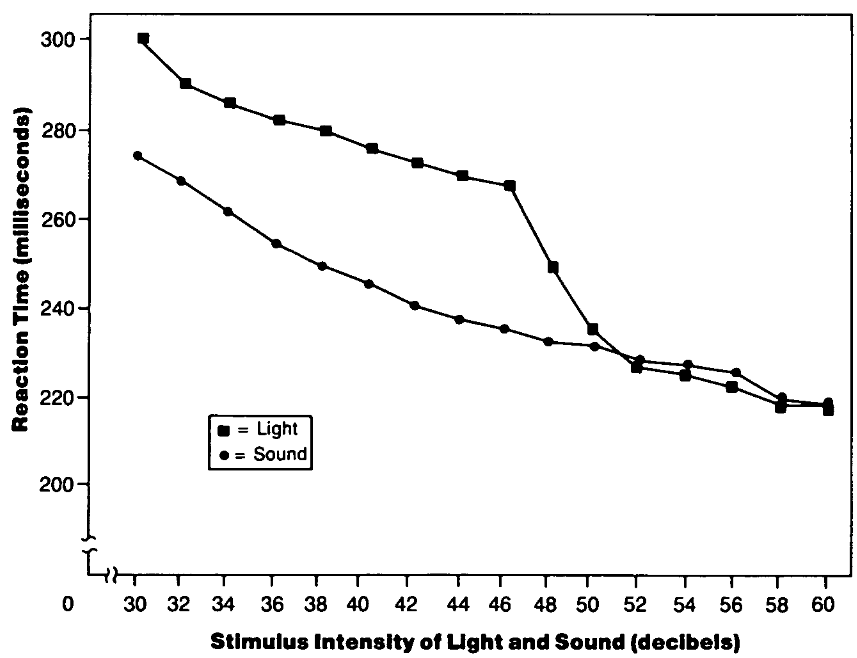


Figure 2. Mean reaction time as a function of stimulus intensity for light and sound (Exp. 2). (From Ref. 3)

11.405 Visual Warning Signals: Effect of Visual Field Position and Color

Key Terms

Alerting systems; color coding; conspicuity; information portrayal; peripheral vision; reaction time; response time; signal detection; signal location; visual signals; warnings

General Description

For foveal presentations, reaction time (RT) is more rapid for offset than for onset, and for a visual signal located in the bottom area of the viewing direction than for one in the top area. There is no significant effect for color of signal in the Ref. 4 study; however, signal color effects under colored ambient illumination are reported (CRef. 11.406).

Methods

Test Conditions

- Two lights, 5.715 cm apart in vertical alignment
- Light color (red, green) condition factorially crossed with light portion (top, bottom) and two critical states (green-onset, red-offset; green-offset, red-onset)
- Conditions randomly assigned in blocks
- Push-button response switch located 2.54 cm below each light
- Display presented foveally, 71.12 cm in front of observer
- Low-ambient illumination and 60 dB (SPL) random noise masking of extraneous sounds

Experimental Procedure

- Between-subjects, randomized block design
- Independent variables: color signal of light, position signal of light, onset-offset of signal light
- Dependent variable: response time between signal onset/offset and observer's response
- Observer's task: monitor a display and press a designated switch in response to designated signal (a "watch-keeping" task)
- Four groups of 32 enlisted men each as observers; age range of 17-24 yrs; no experience in "watch-keeping" tasks

Experimental Results

- Signal offset is detected faster than onset (0.95 versus 1.03 sec) ($p < 0.01$).
- A bottom signal is detected faster than a top signal (0.97 versus 1.01 sec) when located one degree below eye level ($p < 0.01$).
- No statistically significant difference is found between detection times for red or green signals under these specific test conditions.

Repeatability/Comparison with Other Studies

Faster offset RTs represent a reversal of previous warning-light results. However, signal lights in previous studies were presented when observers were performing additional tasks, and the signal lights were presented in peripheral vision rather than foveal vision.

Constraints

- No additional tasks were assigned to observers; results may differ if more realistic tasks were given to observers in addition to monitoring signals.
- Either onset of one light or offset of another light could occur. Results might differ if both lights had the same type of designated signal (either onset or offset).
- Whether RT is faster for onset or offset of a light may depend on whether the light is presented in foveal or peripheral vision. Results across studies indicate that RT may be faster for onsets in peripheral vision and for offsets in foveal vision.

Key References

1. Adams, J. A., & Boulter, L. R. (1964). Spatial and temporal uncertainty as determinants of vigilance behavior. *Journal of Experimental Psychology, 67,* 127-131.

2. Alluisi, E. A., Chiles, W. D., & Hall, T. J. (1964). *Combined effects of sleep loss and demanding work-rest schedules on crew performance* (AMRL-TDR-64-63). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory. (DTIC No. AD606214)

3. Pease, V. P., & Sticht, T. G. (1965). Reaction time as a function of onset and offset stimulation of the fovea and periphery. *Perceptual Motor Skills, 20,* 549-554.

*4. Warm, J. S., Loeb, M., & Alluisi, E. A. (1967). Effects of color, relative position, and the onset or offset of signals in a watchkeeping task. *Psychonomic Science, 9,* 95-96.

Cross References

7.513 Search time: effect of number of colors and information density;

7.519 Search time: effect of color coding;

11.204 Use of color coding: effect of visual field location;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue;

11.406 Visual warning signals: effects of background color and luminance;

11.408 Master warning signals: effect on detection of signals in the visual periphery

Notes

11.406 Visual Warning Signals: Effects of Background Color and Luminance

Key Terms

Alerting systems; cautions; color displays; target recognition; visual signals; warning detection; warnings

General Description

Response to a signal light is affected by signal color, background color, and level of ambient illumination. The relative effectiveness of a set of signal colors depends on the measure used—speed of detection (reaction time) or accuracy of color identification. However, for both measures, performance for red and green signals is better than performance for yellow and white. Detection and color identification are more difficult under bright ambient illumination.

Methods

Test Conditions

- Nine red, green, yellow, or white signal lights were arranged in a 3 × 3 matrix with 38 cm separating rows and columns; the output of each light was channeled into a sheet of rippled Plexiglas where it subtended 2 min of visual angle at viewing distance of 4 m; intensities of the lights were closely matched
- Plexiglas backgrounds were either dark green, blue, tan, or copper, with the colors spectrographically matched to natural-background colors; under bright-light ambient conditions, dark green, blue, tan, and copper yielded luminances of 27, 6, 3, and 1 cd/m^2, respectively; under dim-light ambient conditions, all background colors yielded luminance of less than 0.3 cd/m^2
- Response panel directly in front of observer with nine switches arranged in 3 × 3 array corresponding to nine signal lights; switches thrown by preferred hand
- 2.54-cm red light at top of surround flashed as ready signal; similar green light, also at top of surround, was illuminated simultaneously with one of the nine signal lights; when subject pressed correct response button, green light went off and red light again came on

Experimental Procedure

- Within-subjects design with repeated measures on ambient illumination light color conditions
- Independent variables: signal light color, background color, ambient illumination, sex of subject
- Dependent variables: reaction time, measured from onset of signal light until correct switch was pressed; percentage error in color identification
- Subject's task: press switch on response panel corresponding to location of signal light; name color of signal light
- 24 male and 24 female college students, balanced across groups and screened for normal acuity and color vision

Experimental Results

- Reaction time for each signal color is significantly different ($p < 0.01$) from reaction time for every other signal color. The rank ordering of signal colors determined by speed of reaction time (from fastest to slowest) is red, green, yellow, white (Table 1).
- Based on color-naming errors (from least to most), the order of signal colors is green, red, white, yellow (Table 1).
- Reaction time and color-naming errors increase under bright illumination, probably due to reduced brightness contrast between signal and background.
- Under dim light with good brightness contrast, color of signal light has little effect on reaction times.
- Significant interactions are found between signal color, background color, and ambient illumination (Figs. 1, 2).
- Color-naming errors are significantly higher for males than for females ($p < 0.05$).

Variability

There were significant main effects due to color of stimulus ($p < .01$) and level of ambient illumination ($p < .01$). Significant first-order interactions were found between stimulus and background ($p < .01$, Fig. 1, $p < .05$, Fig. 2) and stimulus color and level of ambient illumination ($p < .01$)

Repeatability/Comparison with Other Studies

Reference 1 yielded similar results.

Table 1. Mean reaction times and percentage error. (From Ref. 1)

Factor	Group	Number	Time (Sec)	% Error
Overall		48	2.821	20.17
Sex of Observer	Female	24	2.662	17.53
	Male	24	2.979	22.80
Background Color	Blue	12	2.663	17.59
	Copper	12	2.687	17.71
	Tan	12	2.810	22.22
	Green	12	3.123	23.14
Ambient Illumination	Dim	48	1.313	12.68
	Bright	48	4.328	27.67
Signal Color	Red	48	2.019	8.33
	Green	48	2.341	4.17
	Yellow	48	2.992	43.75
	White	48	3.930	24.42

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Colors used in this study for signal lights and backgrounds may not be appropriate for many applications.
- Subjects received an alerting signal prior to onset of signal light. Results may differ when no alerting signal is used.
- Luminances of the four backgrounds were not equal under the bright condition.
- Lights of different colors having the same intensity are not perceived to be equally bright.
- Color sensitivity of the eye is different in dim versus bright ambient lighting.
- Many other factors, such as location (CRef. 11.408) and size (CRef. 11.409) of signals and performance of concurrent tasks, affect response to visual signals.

Key References

*1. Reynolds, R. E., White, R. M., Jr., & Hilgendorf, R. L. (1972). Detection and recognition of colored signal lights. *Human Factors, 14*, 227-236.

Cross References

7.519 Search time: effect of color coding;

11.202 Redundant coding: use of color in conjunction with other codes;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue;

11.408 Master warning signals: effect on detection of signals in the visual periphery;

11.409 Visual warning signals: effect of size and location

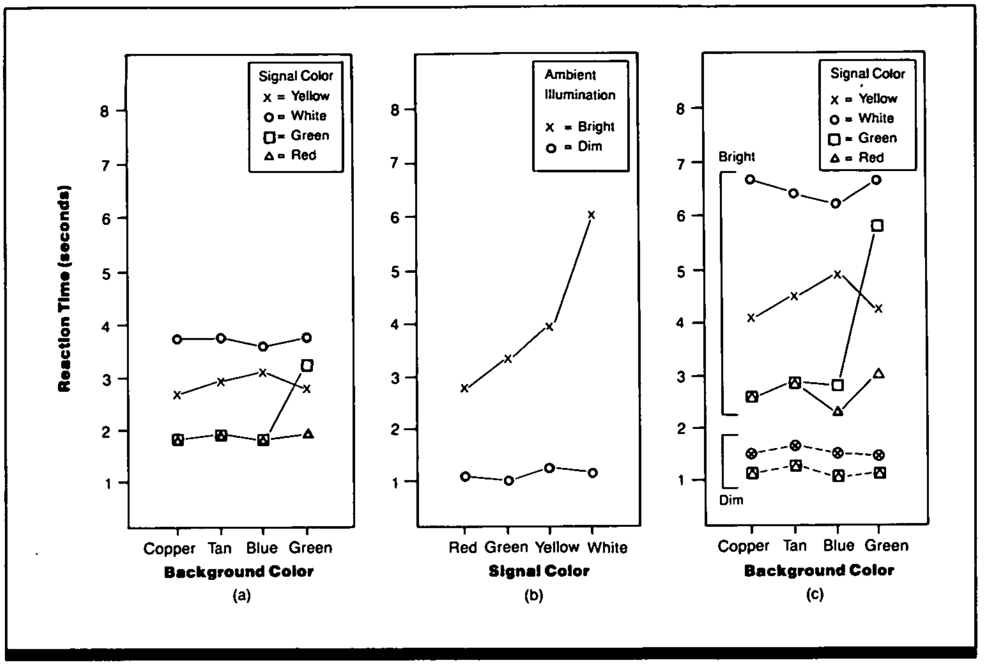


Figure 1. Reaction-time data showing interactions for (a) signal color with background color, (b) signal color with ambient illumination, and (c) signal color with background color and ambient illumination. (From Ref. 1)

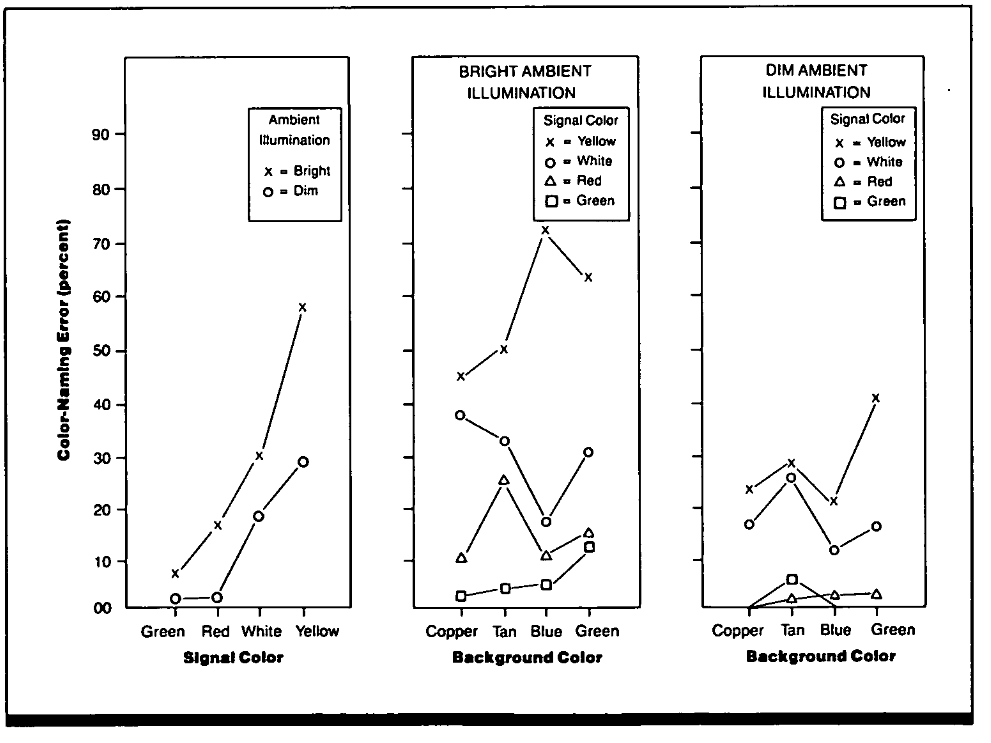


Figure 2. Color-naming error data showing interactions for (a) signal color with ambient illumination, and signal color with background color under (b) bright or (c) dim ambient illumination. (From Ref. 1)

11.407 Visual Warning Signals: Effect of Shape

Key Terms

Alerting systems; cautions; conspicuity; signal shapes; visual signals; warnings

General Description

There is no statistical difference in response time to various simple shapes of warning signals. Subjective preference is for an inverted triangle.

Methods

Test Conditions

Study 1 (Ref. 2)

- Mockup F7U (Cutlass) cockpit with four aviation-red lighting fixtures; midpoints of fixtures at ~81.3-cm (32 in.) distance and at 14, 17, 20, and 23 deg below horizontal eye level
- Inside of lenses painted to yield illuminated circle, square, triangle, or rectangle, each 1.3 cm^2
- RPM meter mounted 12.7 cm above forward panel at normal position of reticle of optical gunsight; needle input function was random and continuous; continuous, rotary control knob for needle mounted on lap board held by subject; telegraph key to extinguish warning signals mounted next to control knob
- Subject's right hand used for both tasks; error feedback given after each block of 16 trials (one indicator light per trial)
- For night conditions in Exp. 1, cockpit dials illuminated at 3.4 cd/m^2; warning signals presented at 2055.6 cd/m^2
- For day conditions in Exp. 1, cockpit-environment illuminance was ~290.6 lux and the signal luminance at 2055.6 cd/m^2
- Subject dark adapted for 15 min before first trial of each night condition and light adapted for 5 min before first day-condition trial
- For Exp. 2, signal brightness was 8.6 cd/m^2 for night conditions and 20.6 cd/m^2 for day conditions; other variables were the same as for Exp. 1
- Two stimulus presentation modes: steady and blinking

Study 2 (Ref. 1)

- Nineteen different shapes presented in pairs via slide projector; shapes were white with thin black border on gray background; each shape had approximately the same area (size not reported)
- Pairs of different and same shapes presented on gray background via slide projector
- All shapes factorially combined with each other
- Each shape presented on left and right side of stimulus pair
- Stimulus pairs presented in random order
- All shapes of approximately equal area (size not reported)

Experimental Procedure

Study 1

- Independent variables: signal shape, maximum (Exp. 1) and minimum (Exp. 2) contrast conditions, mode of presentation, surround brightness, signal position
- Dependent variable: response time measured from signal onset until key press by subject
- Subject's task: primarily to adjust control knob for RPM-meter needle (compensatory tracking task), and secondarily to extinguish illuminated signal by pressing telegraph key
- 10 enlisted men for each experiment; 5 of the subjects participated in both experiments

Study 2

- Two alternative-forced choice
- Within subjects design
- Independent variable: shape of signal
- Dependent variable: subjective preference, measured in terms of relative frequency of preference
- Subject's task: indicate which shape of each pair was preferred shape for a warning signal
- 54 male and 12 female college students, unpaid volunteers aging 18-29 yrs.

Table 1. Mean response times (in milliseconds) as a function of warning signal characteristics (Study 1). (Data from Ref. 2)

Variable	Exp. 1 Mean	Exp. 2 Mean
Shape		
circle	680	1635
square	693	1649
triangle	690	1690
rectangle	693	1641
Position		
1 (top)	682	1701
2	690	1593
3	692	1663
4 (bottom)	692	1657
Surround		
light (day)	689	1607
dark (night)	690	1700
Steady-Blink		
steady	682	1296
blink	697	2011
Grand Mean	689	1654

Experimental Results

Study 1

- Response time to warning lights is not dependent upon shape of signal light, or upon signal location, surround brightness, or whether signal light was steady or blinking.

Study 2

- Equilateral triangle on its point is the preferred warning shape.
- A shape oriented on its points is preferred over that shape oriented on its base.

Variability

Study 1 used analysis of variance. Study 2 used nonparametric analysis.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

Study 1

- Only one light illuminated per trial; therefore interactions were not addressed.
- Order of trials was always (Trials 1-64) nights conditions and steady lights, (Trials 65-128) day conditions and flashing lights, (Trials 129-192) day conditions and steady lights, and then (Trials 193-256) night conditions and flashing lights.

Study 2

- Shapes presented were not illuminated lights.

Key References

*1. Riley, M. W., & Cochran, D. J., & Ballard, J. L. (1982). An investigation of preferred shapes for warning labels. *Human Factors, 24*(6), 737-742.

*2. Siegel, A. I., Fox, B. H., & Stirner, F. W. (1957). *Caution and warning light indicators for naval aircraft: II. An investigation into the effects of varying light shapes on the attention arresting value of caution.* Villanova, PA: Applied Psychological Services.

Cross References

11.207 Display element shape: effect on reading and search times;

11.403 Target coding: effect on search time;

11.409 Visual warning signals: effect of size and location

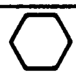
Rank	Shape	Shape number
1		4
2.5		10
2.5		15
4.5		5
4.5		3
6		17
7		18
8.5		2
8.5		13
10		12

Figure 1. Shapes in order of preference. Identical rank values indicate that shapes had the same preference score (Study 2). (From Ref. 1)

11.408 Master Warning Signals: Effect on Detection of Signals in the Visual Periphery

Key Terms

Alerting systems; conspicuity; master warning; peripheral warning signals; reaction time; signal interaction; signal location; visual periphery; visual signals; warning detection; warnings

General Description

Peripherally located warning lights are detected with greater reliability when there is a central master light than when there is no master light (Fig. 1). Peripheral lights nearer the center are detected more quickly than those further away.

Applications

Location and systems arrangement of warning signals in crew system design. Systems integration with high operator response potential in corrective action(s).

Methods

Test Conditions

- Primary task was continuous compensatory tracking of the needles of two milliammeters mounted on forward center panel; each needle controlled by rotary knob below milliammeter; tracking performance feedback given to subject after each eight-run session
- Secondary task was to extinguish peripheral or remote-peripheral light; a master light located centrally on simulator console at 15 deg below horizontal visual axis was or was not simultaneously illuminated; master and peripheral lights extinguished by pressing button below peripheral or remote-peripheral light; all lights of equal brightness
- Nine lights mounted at 30 deg to right and 50 deg down, and 61 cm (24 in.) from eyes (peripheral lights); nine other lights mounted at 95 deg to right and 69 deg down, and 58.4 cm from eyes (remote peripheral lights)
- Subjects wore H-4 crash helmet with 58-H-4 liner and mounted earphones; 15-min dark adaptation for night condition with Naval Air Polaroid dark adaptor goggles
- Day and night conditions approximated by two levels of surround brightness and display intensities (day: 300 fL; night: 0.06 fL)

Experimental Procedure

- Mixed factorial design
- Independent variables: surround brightness and display intensities (day or night conditions), location of peripheral lights, illumination or non-illumination of master light
- Dependent variable: reaction time, measured from onset of light to button press (RTs >4.75 sec assigned values of 5 sec and counted as misses)
- Subject's task: primarily keep needles centered on milliammeters and secondarily extinguish light as soon as it was illuminated
- 7 male university students (ages 18-21 yrs.) and 2 male staff personnel

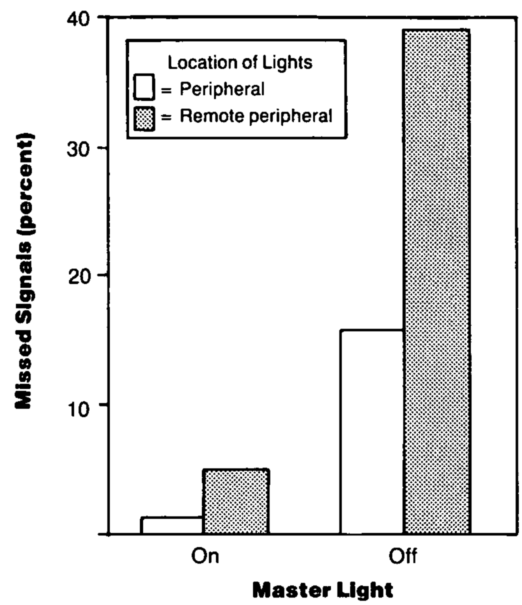


Figure 1. Percentage of missed (RT >4.75 sec) peripheral and remote peripheral lights as a function of illumination of a central master light. (Data from Ref. 3)

Experimental Results

- The response time to peripheral lights is faster with a central master light illuminated (RT = 2.81 sec) than without a master light (RT = 3.31 sec)
- Peripheral lights are detected (i.e., RT <4.75 sec) eight times more often with a central master light illuminated than without a master light (27.4% versus 3.4%; $p < 0.001$).
- RT is faster when the peripheral lights are closer to the center (RT = 2.56 and 2.70 for master light on and off, respectively, versus 3.05 and 3.92 for the remote peripheral lights under the same conditions).
- There is no significant effect of surround brightness level (day or night illumination).

Variability

Analysis of variance and *t*-tests were used. Between-subject variability was significant.

Constraints

- Only two surround brightness and display intensity levels were used, approximating night and day conditions.
- Only peripheral lights mounted to the right of observers were tested; results may be different for left-mounted caution lights. Hand-dominance information was not reported.
- Master light was same brightness and color as peripheral lights; performance may vary if brightness of master and caution lights differs.
- Detection and response times are highly dependent on location within areas of maximum visual acuity, level of operator workload, and signal-presentation characteristics.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. Boucek, G. P., Veitengruber, J. E., & Smith, W. D. (1977). *Aircraft systems criteria study. Vol. II. Human factors guidelines for aircraft alerting systems, Final Report* (FAA-RD-76-222). Washington, DC: Federal Aviation Administration. (DTIC No. ADA043383).

2. Rich, P. M., Crook, W. G., Sulzer, R. L., & Hill, P. R. (1972, March). *Reactions of pilots to warning systems for visual collision avoidance. National Business Aircraft Meeting* (SAE Paper 720312). Wichita, KS: Society of Automotive Engineers.

*3. Siegel, A. I., & Crain, K. (1960). Experimental investigations of cautionary signal presentations. *Ergonomics, 3*, 339-356.

Cross References

7.506 Search time: effects of target conspicuity and fixation eye movements;

11.203 Use of color coding: effect of display density;

11.403 Target coding: effect on search time;

11.405 Visual warning signals: effect of visual field position and color;

11.409 Visual warning signals: effect of size and location;

11.414 Coupling of master indicators with peripherally located warning displays

11.409 Visual Warning Signals: Effect of Size and Location

Key Terms

Conspicuity; CRT displays; head-up displays; visual signals; warnings

General Description

Warning-light size may have little effect under normal operating conditions, but under "worst case" conditions, mean reaction time (RT) and amount of variance decrease as warning-light size increases. However, after the light border becomes wide enough (e.g., 0.48 cm around a 0.32 × 1.78-cm legend), RT levels off and does not further decrease.

For a head-up display, flashing warning messages capture attention better than static messages (CRef. 11.411); an auditory master alerting signal would increase the probability of attending an emergency message (CRef. 11.413). RT decreases until warning-message character height is 1 deg, and then levels off for some messages (Fig. 1).

Table 1. Mean RTs and standard deviations for warning lights with various border widths (and corresponding illuminance values) (Study 1). (From Ref. 4)

Border Width (cm)	Illuminance (lux)	Mean RT (seconds)	Standard Deviation
0.08	0.045	6.11	8.90
0.16	0.128	2.49	3.09
0.32	0.269	1.60	2.31
0.48	0.538	1.18	1.99
0.63	0.807	0.71	0.24
0.79	1.022	0.73	0.28

Methods

Test Conditions

Study 1 (Ref. 4)

- Subject seated in F-1E Flight Simulator with "worst case" lighting (high ambient light conditions, dimmed warning lights, and instrument panel and "thunderstorm" lights at maximum brightness as if plane had just come out of dark clouds into bright sunlight)
- Cockpit in center of 7.3-m (24 ft) diameter Spritz Sky Dome with three 1.6 cm (5/8 in.) stimulus lights located on dome, one in front of cockpit and one 30 deg (1.8m) on each side of center light
- Six red warning lights mounted 2.54 cm below cockpit glare shield and 71.12 cm from subject's eye position; each light had legend represented by black opaque tape 0.32 cm high and 1.78 cm long; size of illuminated border around legend varied by mask over face of light; border width was 0.08, 0.16, 0.32, 0.48, 0.63, or 0.79 cm with corresponding luminances of 0.045, 0.128, 0.269, 0.538, 0.807, or 1.022 lux
- As primary task, subject scanned dome lights and pressed trigger switch as soon as one of the lights came on; as secondary task, subject pressed button with left thumb as soon as a warning light came on

Study 2 (Ref. 7)

- A-7E head-up display (HUD) without dynamic elements in a simulated cockpit; real-world view provided by color motion picture
- Subject's workload level maintained by two-dimensional compensatory tracking task similar to pilot's flight task
- One of three red warning messages (SAM HI, FIRE, HYD PRESS) varied in size (0.5, 1, and 2 deg) and location (11 possible locations); 3:2 height-to-width ratio, 10:1 height-to-stroke ratio, 0.5-character-height spacing between characters; three message conditions (messages and other symbols at 4.08 cd/m^2, messages brighter at 8.16 cd/m^2, or messages red and other symbols green)
- 400-Hz fan noise used to block auditory equipment cues
- Message exposure limited to .033 sec (.004 rise and decay times) to force performance differences within subjects; if no response after 4 sec, message would flash at 3 Hz

Experimental Procedure

Study 1

- Independent variables: size of illuminated border around tape representing legend
- Dependent variable: RT
- Subject's task: primarily to scan three lights on dome and press trigger switch at onset of light, and secondarily to press button when one of the warning lights came on
- 4 Navy enlisted men (ages 20-25) with normal color vision, normal (or corrected) visual acuity and some practice in the task

Study 2

- Independent variables: wording of message, character size, location, message condition (e.g., relative brightness)
- Dependent variable: RT, message misses, and response errors
- Subject's task: primarily to move joystick so that aircraft symbol stayed centered in box, and secondarily to press button when a warning message was detected
- 6 male nonpilot personnel screened for uncorrected normal foveal and peripheral vision, normal color vision and depth perception; subjects had some practice on the task

Experimental Results

Study 1

- Preliminary sessions indicate that warning-light size has little effect under normal operating conditions.
- Under the "worst case" conditions of the main experiment, mean RT and amount of variance decrease as warning-light size increases (Table 1).
- The smallest effective illumination border around the 0.32 × 1.78-cm legend is 0.48 cm, which corresponds to an illuminance of 0.54 lux.

Study 2

- Flashing (3 Hz) displays (used to indicate misses) capture attention better than static displays (subjects never missed an error indication (CRef. 11.411). Questionnaire data also indicates that an auditory master alerting signal would increase the probability of attending to an emergency message (CRef. 11.413).
- Character heights of <1 deg visual angle yield longer RTs; for two signals (SAM HI and HYD PRESS), RTs do not decrease for larger characters (Fig. 1).

• Performance is best when the visual message is located along the horizon and in the lower half of the visual hemisphere.
• There is a trend for relatively brighter messages to yield better performance than messages of the same brightness as the other symbols. Differentiating warning messages by color (red versus green) yields even better performance, but not one of these differences is statistically significant, i.e., all must be regarded as chance differences.

Variability

Study 1

Analysis of variance performed on reaction speeds (reciprocal of reaction times). Duncan multiple-range test used to determine smallest effective light size (border width).

Study 2

Separate analysis of variance performed for each warning message; size or location or interaction of size and location significant for all analyses.

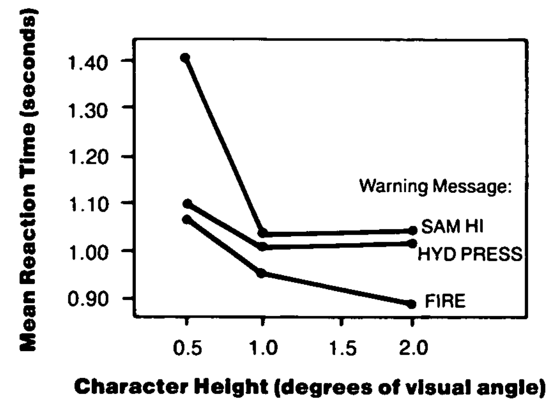


Figure 1. Mean reaction time for three visual warning messages (SAM HI, HYD PRESS, FIRE) as a function of character height (Study 2). (From Ref. 7)

Constraints

Study 1

• Main experiment included only a "worst case" high-ambient light level.
• Decisions about warning-light sizes should draw on information about effect of different light sizes on dark adaptation and visual acuity.

Study 2

• Within-subject differences disappeared when warning messages were not limited to very brief durations; it is unclear what the results would be in actual situations.
• Task demands were limited to the compensatory tracking task and the button-press response to the warning message; in actual practice, subjects would be trained pilots and other stresses would be present.

Key References

1. Berson, B. L., Po-Chedley, D. A., Boucek, G. P., Hanson, D. C., & Leffler, M. F. (1981, January). *Aircraft alerting systems standardization study. Vol. II. Aircraft alerting system design guidelines* (Tech. Rep. No. FAA/RD-81/38/2). Washington, DC: Federal Aviation Administration. (DTIC No. ADA043383)

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*4. Merriman, S. C. (1969, February), Operational attention-intrusion effects associated with aircraft warning lights of varied size. Warminster, PA: Naval Air Development Center, NADC-AC-6901. (DTIC AD-849165)

5. MIL-STD-411, *Aircrew Station Signals*. Washington, DC: U.S. Department of Defense.

6. MIL-S-38039A, *Systems Illuminated, Warning, Caution, and Advisory*. Washington, DC: U.S. Department of Defense.

*7. Sheehan, D. J. (1972). *Head-up display warning requirements research* (Tech. Rep. NR-213-086). Arlington, VA: Office of Naval Research, Department of the Navy. (DTIC No. AD755736)

Cross References

7.511 Search time and eye fixations: effects of symbol color, size and shape;

11.403 Target coding: effect on search time;

11.405 Visual warning signals: effect of visual field position and color;

11.411 Visual warning signals: effect of flashing;

11.413 Coupling of visual and auditory warning signals: effects on detection and recognition;

11.414 Coupling of master indicators with peripherally located warning displays

11.410 Alerting Signals in the Peripheral Visual Field: Use of Apparent Motion

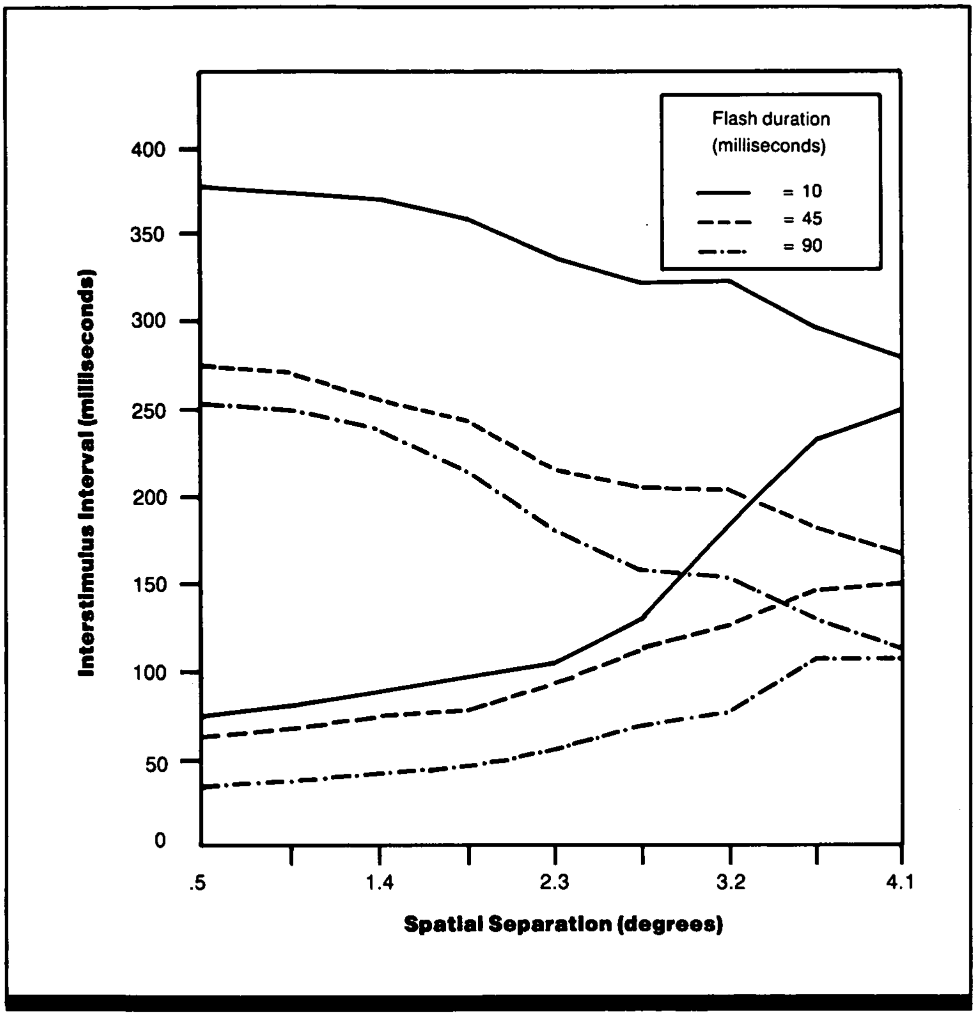

Figure 1. The region between the upper and lower curves of each pair defines conditions that produce apparent motion of two lights. Above the upper curve the lights appear to illuminate in succession. Below the lower curve the lights appear to illuminate simultaneously. (From Ref. 2)

Key Terms

Alerting systems; apparent movement; critical flicker fusion; flashing lights; flicker fusion frequency; peripheral vision

General Description

Two alternately flashing lamps placed a slight distance apart may result in the phenomenon known as stroboscopic apparent motion. If the stimuli are presented in the retinal periphery, the illusion is quite compelling, and the motion perceived may extend beyond the distance separating the lamps. Such apparent motion may be highly effective as an attention-getting mechanism. Figure 1 describes the temporal and spatial parameters required to produce or inhibit apparent motion for three flash durations. For each pair of curves, the region between the upper and lower curves defines the separation between lights and the onset-to-onset intervals that produce good apparent motion. Regions above the upper curves define the conditions under which the two lights appear to flash separately, but with no apparent motion. Regions below the lower curves define the conditions under which the two lights appear to be illuminated simultaneously.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Two achromatic lights; illuminance not reported but sufficient for easy visibility, spatial separations of 0.5, 0.95, 1.4, 1.85, 2.3, 2.75, 3.2, 3.65, 4.1 deg of visual angle
- Onset-to-onset intervals of 0-400 msec
- Flash durations of 10, 45, 90 msec
- Ambient illuminance not reported

Experimental Procedure

- Method of limits
- Independent variables: spatial separation, temporal separation, flash duration
- Dependent variable: verbal reports of apparent motion versus simultaneous or successive illumination
- Observers varied in extent of practice

Experimental Results

- Apparent motion is seen over a wide range of onset-to-onset intervals for three flash durations and separations between lights.
- The figure may be used to establish tradeoff parameters. For example, if signals are 45 msec in duration, separated by 1.4 deg, flashes will appear simultaneous for onset-to-onset intervals of 0-125 msec, and movement will appear for intervals of 125-300 msec. Above 300 msec, the two lights will appear to illuminate successively.

Variability

No information on variability was given.

Constraints

- Various other factors, such as stimulus intensity and size of inducing stimuli, may affect perceived motion.
- Apparent motion may be more effective as an attention-getting device than a single flashing lamp. However, if two adjacent warning lamps begin to flash at the same time, their alternate flashing may be seen as a single moving lamp. Since this might lead to action for only one warning condition when action for both is required, spatial and temporal parameters need to be arranged so that motion is not perceived and the separate flashing of the two lamps is seen.

Key References

1. Graham, C. H. (1965). Perception of movement. In C. H. Graham (Ed.), *Vision and visual perception* (pp. 575-588). New York: Wiley.

*2. Kolers, P. A. (1977). *Aspects of motion perception*. New York: Pergamon Press.

3. Neuhaus, W. (1930). Experimentelle Untersuchung der Scheinbewegung. *Archiv fur Gesamte Psychologie, 75*, 315-458.

4. Sperling, G. (1976). Movement perception in computer-driven visual displays. *Behavioral Research Methods and Instrumentation, 8*, 144-151.

5. Thorson, J., Lange, G. D., & Biederman-Thorson, M. (1969). Objective measure of dynamics of a visual movement illusion. *Science, 164*, 1087-1088.

Cross References

1.637 Contrast sensitivity: effect of target motion;

5.203 Factors affecting threshold for visual motion;

5.205 Perception of motion in the visual periphery;

5.206 Sensitivity to direction of motion in the visual periphery;

5.403 Temporal and spatial relationships in visual apparent motion;

11.402 Alarm classification and development

11.411 Visual Warning Signals: Effect of Flashing

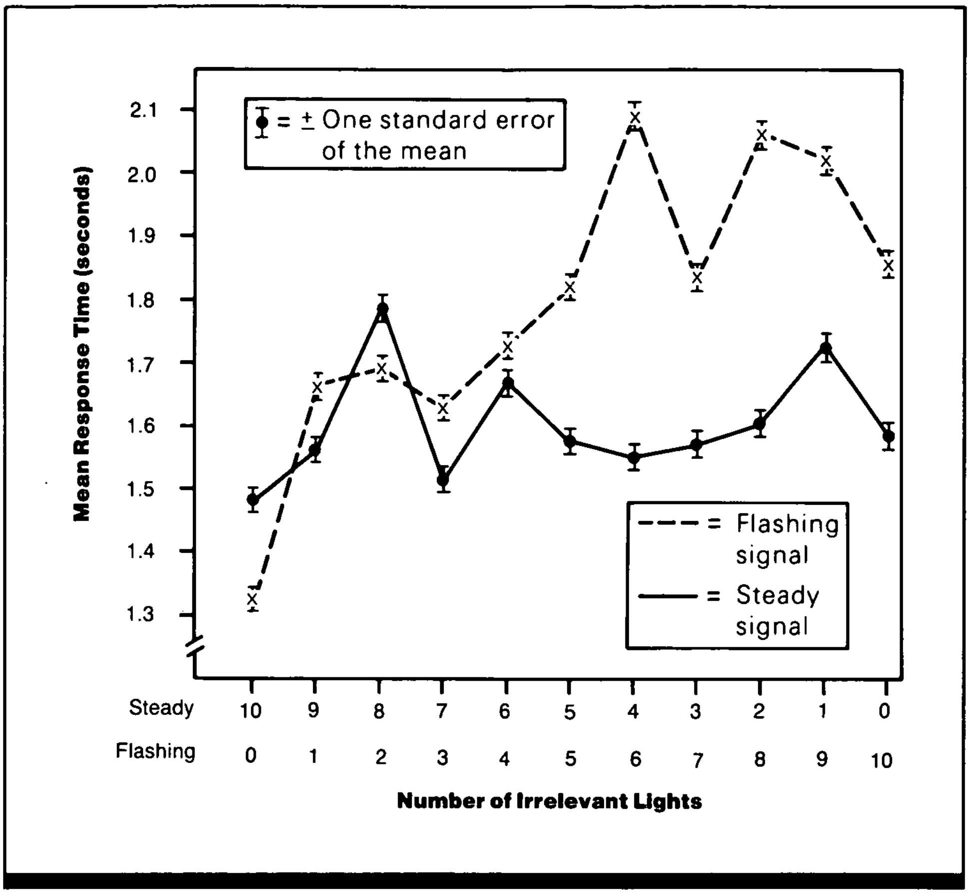

Figure 1. Mean reaction time for a steady or flashing signal light as a function of the ratio of steady and flashing irrelevant background lights. (From Ref. 4)

Key Terms

Conspicuity; flash rate; flashing lights; reaction time; visual signals; warnings

General Description

Flashing signal lights are detected more quickly than steady signals when all other (background) lights are steady, but the advantage is lost if even one background light is flashing. If more than half of the background lights are flashing, the **reaction time** (RT) for a flashing signal is >250 msec longer than the RT for a steady signal.

Methods

Test Conditions

- Matte-white background formed arc around subject at center with 1.52 m (5 ft) radius (horizontal angle of 92 deg and vertical angle of 44 deg); uniformly lighted (3.43 cd/m^2) background divided into 15 equal areas by 2.54 cm black lines
- Six amber signal lights and two red and two green irrelevant lights in each area; brightness of each light was approximately equal
- Fifteen response buttons configured to reflect the arrangement of the 15 areas of the background; press of response button extinguished respective signal light but not irrelevant light
- One signal light and 10 irrelevant lights on at any instant
- Sixty total irrelevant lights of which ten were on at any one time; irrelevant lights were "on" in ten different proportions: from ten flashing and zero steady to zero flashing and ten steady; signal may or may not be flashing; two or three phases used to control irrelevant lights so that not all flashed in unison; both appearance of signal and rearrangement of irrelevant lights occurred 20 times per minute (on average)
- 100 signals presented in each trial; 20 trials: two signal conditions (steady, flashing) and ten irrelevant steady-flashing light combinations

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Procedure

- Independent variables: steady or flashing signal light, ratio of steady to flashing irrelevant lights
- Dependent variables: reaction time to extinguish amber signal light, errors of commission (press wrong button), errors of omission (failure to respond to signal within nine sec)
- Subject's task: press appropriate button to extinguish amber light
- 4 subjects with extensive practice

Experimental Results

- Reaction times are shorter when all the irrelevant lights are steady, and shortest when the signal is flashing and all irrelevant lights are steady.
- The advantage for a flashing signal is lost if even one irrelevant light is flashing; if at least half of the irrelevant lights are flashing, the reaction time for a flashing signal is >250 msec longer than for a steady signal.
- Analysis of the wrong buttons pressed and of the signals missed show no significant trends because subjects make few errors.

Variability

An analysis of the variance was carried out; there were significant between-subject differences ($p < 0.001$).

Repeatability/Comparison with Other Studies

A previous study by Crawford (Ref. 3) also investigated flashing or steady background of lights and yielded similar results.

Constraints

- The subjects were not performing other tasks during the experiment, whereas machine operators would normally have other tasks.
- Colors of irrelevant lights were always red or green.
- Only amber signal lights were used.

Key References

1. Berson, B. L., Po-Chedley, D. A., Boucek, G. P., Hanson, D. C., & Leffler, M. F. (1981, January). *Aircraft alerting systems standardization study Vol. II - Aircraft alerting design guidelines.* (Tech. Rep. No. FAA/RD-81/38/2). Washington, DC: Federal Aviation Administration. (DTIC No. ADA106732)

2. Boucek, G. P., Veitengruber, J. E., & Smith, W. D. (1977, May). *Aircraft alerting systems criteria study Vol. II. Human factors guidelines for aircraft alerting systems.* (Tech. Rep. No. FAA-RD-76-222-2). Washington, DC: Federal Aviation Administration. (DTIC No. ADA043383)

3. Crawford, A. (1962). The perception of light signals: The effect of the number of irrelevant lights. *Ergonomics, 5,* 417-428.

*4. Crawford, A. (1963). Perception of light signals: The effect of mixing flashing and steady irrelevant lights. *Ergonomics, 6,* 287-294.

Cross References

11.405 Visual warning signals: effect of visual field position and color

11.412 Deceleration Warning Lights for Motor Vehicles

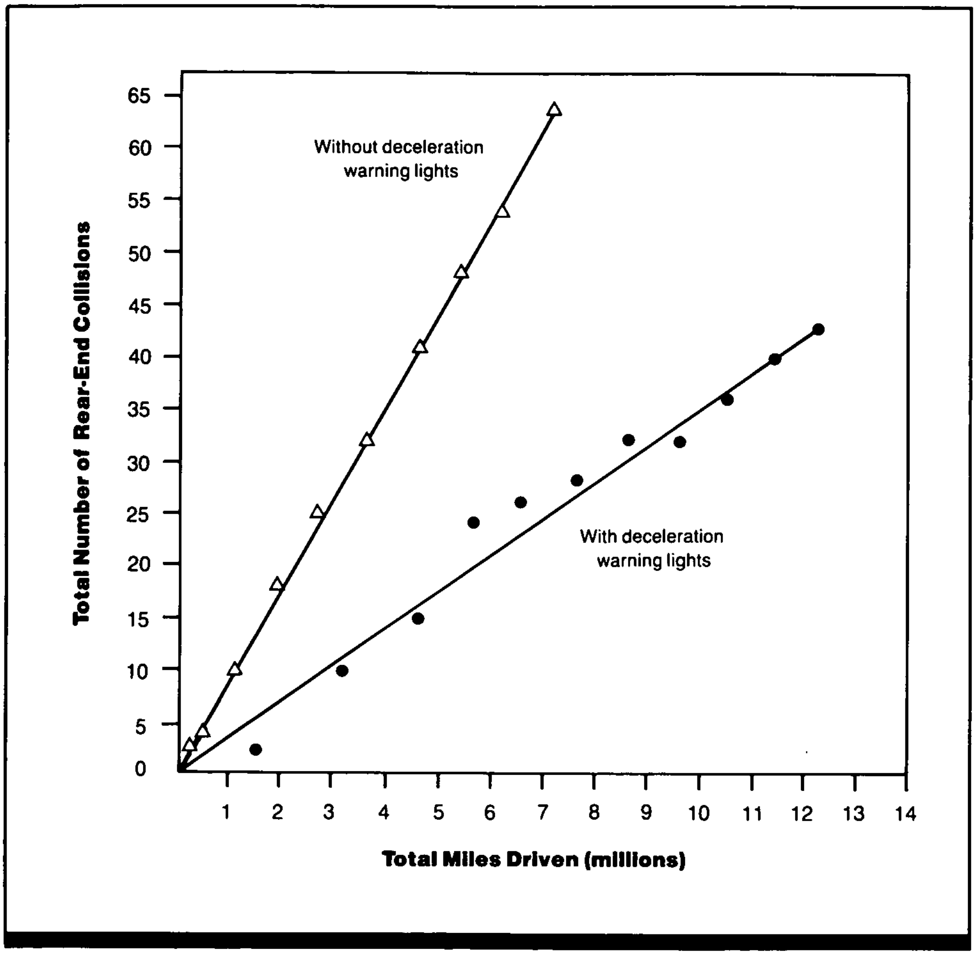

Figure 1. Number of rear-end collisions of taxis with and without deceleration warning lights. (From Ref. 4)

Key Terms

Alerting systems; flash rate; safety; temporal frequency; warnings

General Description

An amber deceleration warning light was added to the rear of a sample of taxicabs driven in a large metropolitan area for a 1-year period in 1972-1973. The flash rate of the light increased exponentially with the rate of deceleration of the vehicle during braking. Rear-end collisions were reduced by 60% for taxicabs with the deceleration light compared to cabs equipped only with normal brake lights.

Applications

A flashing signal will attract operator attention, and flash rate may be useful to indicate the degree of importance of the signal. However, the use of flash rate to convey information must never interfere with the perception of other flashing indicators used, for example, to indicate an emergency condition.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Methods

Test Conditions

- Amber deceleration light mounted equidistant between brake lights and at same height as brake lights on rear of 343 taxicabs, brake-pedal activated; size and luminance not given
- 160 vehicles without warning light
- Flash-rate frequency range of 1.0-7.6 flashes per sec; 50% increase in flash rate for each 0.1 deceleration gravity force increase from 0-0.5 gravity
- Data collected from March 1972 - February 1973
- Same drivers assigned to warning-light-equipped and non-equipped vehicles
- Limited news coverage at start of experiment; no formal public education program; no formal taxi driver education program

Experimental Procedure

- Independent variable: presence versus absence of deceleration light
- Dependent variables: number of rear-end collisions (taxicabs struck by other vehicles) per million miles driven, dollar cost of damage repair per 10^6 mi driven, personal injuries to drivers per million miles
- Subject's task: operate taxicabs in routine manner in a large city
- Number, sex, age, and other subject characteristics not specified; all drivers of taxi firm participated

Experimental Results

- Taxis with deceleration warning signals traveled 12.3×10^6 mi with 3.51 collisions/10^6 mi. Taxis without the warning signals traveled 7.2×10^6 mi with significantly more collisions (8.91 collisions/10^6 mi.) ($p = 0.006$).
- Collision repair costs average \$398/10^6 mi driven for taxis with warning signals and \$1,041/10^6 mi for vehicles not signal-equipped.
- Driver personal injuries are 61.1% fewer with vehicles equipped with deceleration warning signals.

Variability

No information on variability was given.

Constraints

- Although flashing lights are attention-getting (Ref. 1), flash rate per sec is a limited information coding method (Ref. 2).
- Size, illuminance, flash duration, and other warning signal characteristics were not reported (Ref. 4).
- The data were collected in a motoring environment and should be applied cautiously to other environments.
- The experiment did not test the effects of a non-flashing warning light, constant flash rate regardless of rate of deceleration, or multiple warning signals occurring simultaneously or in close conjunction.

Key References

1. Crawford, A. (1963). The perception of light signals: The effect of mixing flashing and steady irrelevant lights. *Ergonomics, 6*, 287-294.

2. Goldstein, D. A., & Lamb, J. C. (1967). Visual coding using flashing light. *Human Factors, 9*, 405-408.

3. Smith, S. L., & Goodwin, N. C. (1971). Blink coding for information display. *Human Factors, 13*, 283-290.

*4. Voevodsky, J. (1974). Evaluation of a deceleration warning light for reducing rear-end automobile collisions. *Journal of Applied Psychology, 59*, 270-273.

Cross References

11.411 Visual warning signals: effect of flashing

11.413 Coupling of Visual and Auditory Warning Signals: Effects on Detection and Recognition

Table 1. Test of critical difference among master cautionary indicators by task levels. (From Ref. 2)

Type of master signal	One-meter task			Three-meter task		
	BII	AI	AII	BII	AI	AII
BI	0.52*	0.58*	1.09**	0.72**	0.82**	1.27**
BII	—	0.06	0.57*	—	0.10	0.55*
AI	—	—	0.57*	—	—	0.45*

Table shows results of a test of critical difference (Ref. 1) evaluating whether time to respond to the peripheral visual test signal differed significantly between each pair of warning signal conditions as indicated.

BI = Brightness level I; BII = Brightness level II; AI = One-tone auditory; AII = Two-tone auditory.

Significance levels are indicated as follows:
*p <0.01 **p <0.001

Key Terms

Auditory warnings; cautions; legend lights; non-verbal auditory signals; verbal signals; visual signals; warnings

General Description

The use of a two-tone, warbling, master warning signal yields faster reaction times than a one-tone master or visual master alone; for a heavier workload, it also yields fewer misses than a one-tone auditory master. Light signals brighter than the environment are better than those at the same brightness as the environment.

Applications

Design of crew system warning systems; determining types of master caution signals in relation to task load.

Methods

Test Conditions

- Primary task was a **compensatory tracking** task with either one or three meters to track; subjects simultaneously had to listen to prose passages with an 83 dB jet-aircraft noise background; subjects had to answer multiple-choice questions about passage at end of each experimental run; combined tracking and test scores yielded a "flight-task proficiency rating" to motivate subject
- Secondary task was to detect peripheral visual signal (e.g., OIL HOT in red against black background) and press associated button to turn off signal; peripheral display was 20 deg to right of center, 46 deg down, and 61.1 cm (24 in.) from subject's eyes; each signal was 3.18 × 0.79 cm; bank of response buttons directly forward and 50 deg down with legend beside each button
- Lighting simulated night conditions, including red illumination usually found in military aircraft; subjects were dark adapted for 15 min with Naval Air Polaroid dark adaptor goggles
- Master warning signals of 1800 Hz complex tone (8 per sec, 25% duty cycle), 83 dB alternating 340 Hz (75% duty cycle) and 1800 Hz (25% duty cycle) complex tones "warbling" at 8 per sec, or yellow Dialight fixture at either 0.58 or 2.67 cd/m^2; master and peripheral visual signals of equal brightness and, if master used, illuminated simultaneously; visual master directly forward of subject, 15 deg down from horizontal visual axis and 71.1 cm away from eyes
- Task difficulty hard or easy; type of master signal: low or high brightness for visual, one- or two-tone for auditory

Experimental Procedure

- Independent variables: task difficulty, type of master signal
- Dependent variable: reaction time
- Subjects' task: primarily compensatory tracking of one or three indicator displays and answer questions about prose passages; secondarily, to press button to extinguish peripheral warning signal
- 12 male university students, with some or no practice

Experimental Results

- Reaction times are shortest for the two-tone master auditory signal (p <0.01 or p <0.001).
- One-tone signal and the brighter master light have shorter reaction times than the dimmer light (p <0.01 for one meter; p <0.001 for three meters).
- One-tone signal and brighter light are equally effective.
- In the three-meter task, there were fewer misses for the bright visual signal and the two-tone auditory signal than for the one-tone auditory signal (p <0.05 and p <0.02, respectively).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Variability

Analysis of variance and tests of critical difference (Ref. 1) were used. There were significant between-subject differences.

Constraints

- Only two levels of flight-task difficulty were used; results may vary for other task difficulty levels.
- Only night conditions were simulated; results may vary for different lighting conditions.

Key References

1. Lindquist, E. F. (1953). *Design and analysis of experiments in psychology and education*. New York: Houghton-Mifflin.

*2. Siegel, A. I., & Crain, K. (1960). Experimental investigations of cautionary signal presentations. *Ergonomics, 3*, 339-356.

3. Staff, Applied Psychological Services, & Lazo, J. (1958, 6 June). *The application of recent research to aircrew station signaling indicator systems* (TEDNAM EL-52004, Part 20, NADC-ACEL-377, pp. ii - 14). Philadelphia, PA: Naval Air Material Center.

Cross References

11.408 Master warning signals: effect on detection of signals in the visual periphery;

11.414 Coupling of master indicators with peripherally located warning displays;

11.419 Coupling of visual and aural warning signals: effect on eye fixation and response time;

11.421 Integration of visual and auditory alerts in warning systems

11.414 Coupling of Master Indicators with Peripherally Located Warning Displays

Key Terms

Alerting systems; cautions; signal colors; warnings

General Description

A centrally located master indicator decreases response time when used in conjunction with peripherally located warning signals. Positive displays, with opaque lettering against a lighted background, are more effective as legends for master indicaters than are negative displays. Larger legend sizes result in significantly lower response times to the onset of the warning display. For a master indicator legend with opaque lettering/lighted background, located 71 cm (28 in.) from the observer, a legend height of 0.635 cm provided the most rapid response to the onset of peripheral warning signals.

Applications

Design of caution and warning light indicator systems in military crew systems.

Methods

Test Conditions

- Yellow master indicator light located 71 cm from subject, 15 deg down from eye-level horizontal
- Bank of aviation-yellow caution indicators (located 20 deg to the right, 46 deg down from horizontal and 61 cm from observer's eyes); set at the same luminance as master indicator light
- Luminances for all lights determined by setting effective contrast differential minimally above recognition threshold, but high enough to ensure discrimination and response within 6 sec for average of four trained judges
- Three legends (digits "5," "6," and "8") on master indicators, with legend heights of 0.317, 0.635, or 0.952 cm; height to width ratio 5:3; stroke width was 12% of digit height
- Positive display of opaque digit, illuminated background; negative display of illuminated digit, opaque background (the legend sizes and background area were the same for positive and negative conditions)
- Night cockpit conditions simulated with aviation-red flood illumination that provided 0.21 cd/m^2 (0.06 fL) luminance on displays; six constantly illuminated aviation-red fixtures mounted near bank of indicator lights
- Individual peripherally mounted caution lights simultaneously presented when master indicator light was turned on
- Three meters for "flight task" compensatory tracking (straight ahead and 25 deg down, 27 deg left and 22 deg down, and 42 deg left and 52 deg down); 71 cm from observer's eyes to meters
- Three banks of nine push buttons each (one forward and two aft); each button extinguished a warning light at same position on bank of indicator lights; observer used bank of buttons identified by digit legend on illuminated indicator light
- 15 min dark adaptation with goggles prior to experimental session
- Observer wore crash helmet with earphones
- Extra monetary rewards for good performance

Experimental Procedure

- Independent variables: master indicator on or off, positive or negative indicator display, legend size
- Dependent variable: response time
- Observer's primary task: maintain three meter needles at central position by adjusting knobs; secondary task to extinguish caution indicator lights by using legend to identify appropriate bank of push buttons and then pressing appropriate button; feedback score provided after each of six experimental runs
- 10 male university students (ages 19-30) with some practice

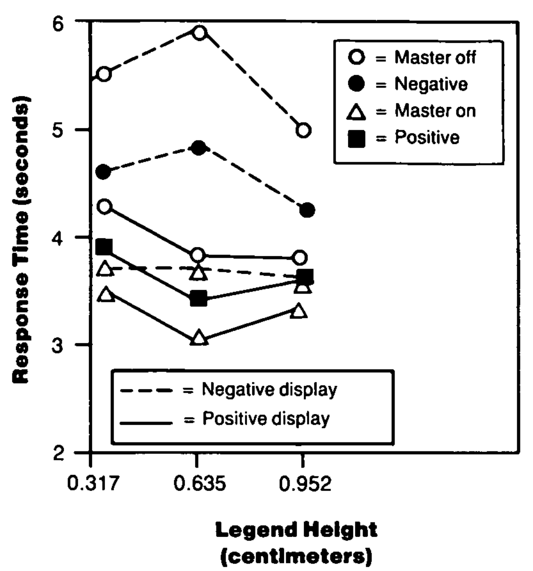

Figure 1. Mean response time data. Filled symbols represent negative (•) and positive (▪) displays combined across conditions. (From Ref. 1)

Experimental Results

- A master indicator lowers response time to caution signals ($p < 0.01$).
- Positive signal legends (opaque letters/lighted background) are more effective than negative signal legends when the signal configurations are identical ($p < 0.01$).
- For positive signal legends, a 0.635-cm legend height is adequate to provide significantly more rapid observer attention-intrusion and reaction/response to the signal presentation ($p < 0.02$) than the 0.317-cm height. For negative signal legends a 0.952-cm legend height yields better performance than the two smaller legend sizes ($p < 0.01$).

Variability

Analysis of variance was conducted.

Repeatability/Comparison with Other Studies

Similar results were reported in Ref. 2 for aviation-red indicator lights.

Constraints

- The peripheral bank of indicators was located only to the right of the observers. Results may have differed for indicators located elsewhere.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance*. AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. Siegel, A. I., & Stirner, F. W. (1957). *Caution and warning light indicators for naval aircraft: IV. Background variation, letter size, and the advantage of a master indicator with yellow cautionary signals in a red illuminated environment*. Villanova, PA: Applied Psychological Services.

2. Stirner, F., Siegel, A., & Fox, E. (1957). *Caution and warning light indicators for naval aircraft: III. An experimental investigation into the advantages of a "master" caution indicator*. Villanova, PA: Applied Psychological Services.

Cross References

7.501 Factors affecting visual search with monochrome displays;

7.511 Search time and eye fixations: effects of symbol color, size and shape;

11.408 Master warning signals: effect on detection of signals in the visual periphery;

11.413 Coupling of visual and auditory warning signals: effects on detection and recognition

11.415 Coupling of Visual and Verbal Warning Signals: Effect on Response Time

Table 1. Averages and ranges of pilot response times (in seconds) recorded for various warning conditions in the F-100F. (From Ref. 2)

Warning Signal	Average & Range of Visual Response Time	Average & Range of Verbal Response Time	Difference	% Improvement w/ Verbal
DC generator failure	Average 10.58 Range 2.0 - 109.9	Average 2.89 Range 1.8 - 4.3	7.69	72.7%
Flight control failure	Average 7.43 Range 1.8 - 57.4	Average 2.81 Range 2.0 - 4.5	4.62	62.2%
Heat and vent failure	Average 34.05 Range 1.8 - 762.4	Average 3.05 Range 2.0 - 5.8	31.00	91.0%
Utility failure	Average 136.98 Range 2.3 - 622.1	Average 3.06 Range 2.0 - 8.1	133.92	97.8%
Fire warning	Average 24.13 Range 2.1 - 110.4	Average 2.76 Range 2.1 - 4.1	21.37	88.6%
AC generator failure	Average 5.68 Range 1.9 - 23.0	Average 2.70 Range 1.8 - 4.1	2.98	52.5%
Oil pressure failure	Average 102.60 Range 1.9 - 458.8	Average 3.38 Range 1.8 - 4.8	99.22	96.7%

Key Terms

Alerting systems; auditory warnings; auditory workload; information cueing; reaction time; verbal warnings; voice warnings; warnings; workload

General Description

Verbal auditory signals used in conjunction with visual signals significantly decrease reaction time when compared to visual signals only. These verbal signals enhance event detection, and can also provide cueing of required operator's corrective action(s).

Methods

Test Conditions

- An operational F-100F was flown on two combat-profile missions, one with standard visual warning equipment and one that also used the auditory-information display (AID); AID provides verbal warning signals via recorded messages
- Seven warning signals shown in Table 1 used in malfunction simulation; no warning lights for Utility Failure and Oil Pressure Failure (gauges only); fire warning activated only red fire warning light in center of main instrument panel; other four warning lights also activated yellow master light in center of main instrument panel
- Pilot told whether actual or test warning after response to warning signal
- Warning signal modality either visual only or visual plus auditory

Experimental Procedure

- Independent variable: warning signal modality
- Dependent variable: response time to acknowledge warnings
- Subject's task: depress switch labeled "Pilot" when a failure signal is detected and the nature of the malfunction is known
- 28 instructor pilots; 22 had flown similar tests in a simulator

Experimental Results

- Response times for visual signals range from 1.8-762.4 sec; response times with added verbal warnings range from 1.8-8.1 sec (Table 1). 33.8% of the response times to visual signals were longer than the maximum response time with a verbal warning.
- With increased visual load during climb, penetration, and low-level phases (Table 2), the response time to visual displays is longer (e.g., 7.13 sec in cruise to 128.27 sec in low-level). The increase in response time with a verbal warning is not as marked (e.g., 2.78 sec in cruise to 3.03 sec in low-level).
- For warnings with gauges only, the average response time is 124.4- sec; with lights, the average response time is 18.92 sec. The corresponding response times, when verbal warnings are also presented, are 3.17 and 2.85 sec, respectively.

Variability

One pilot showed no improvement with the auditory verbal warnings; two improved less than 50%; eight improved from 50-90%; and 15 pilots improved over 90%.

Repeatability/Comparison with Other Studies

- Some studies (e.g., Ref. 1) have not found faster response times when auditory verbal messages were used in conjunction with visual signals; however, Ref. 1 was, in essence, a reaction time study using university students. It should be noted that when the performance of pilots was compared within-subjects for simulator and actual-flight conditions, the simulator data underestimated the advantage of verbal warnings by a factor of three (average advantage for verbal warnings in simulator was 12.22 sec and in flight was 41.12 sec).

Constraints

- Response times to visual warning signals are influenced by the location of the signals, intensity, color, and contrast.
- Response times to auditory verbal warnings are influenced by salience (a female voice is more salient than a male voice in a cockpit).

Key References

1. Bates, A. J., & Bates, C. Jr. (1967). *A comparison of cockpit warning systems* (AMRL-TR-66-180). Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory. (DTIC No. AD655772)

*2. Stroface, J. F., & Starke, R. T. (1963, June). *Operational test and evaluation verbal warning system* (TAC-TR-62-20). Langley AFB, VA: Tactical Air Command. (DTIC No. AD416258)

Cross References

2.301 Factors affecting auditory sensitivity in quiet;

11.402 Alarm classification and development;

11.413 Coupling of visual and auditory warning signals: effects on detection and recognition;

11.416 Comparison of voice and tone warning signals;

11.417 Voice auditory warning signals: effect of alerting tones;

11.418 Voice warning systems: effect of message structure and content;

11.421 Integration of visual and auditory alerts in warning systems

Table 2. Comparison of response times to visual and verbal warning signals (in seconds) during various flight phases. (From Ref. 2)

Flight Phase	Average and Range of Visual Response Times	Average and Range of Verbal Response Times	Difference	% Improvement
Climb out	Average 23.82 Range 1.8 - 278.8	Average 2.92 Range 2.8 - 5.8	20.90	87.7%
Cruise	Average 7.13 Range 1.9 - 57.4	Average 2.78 Range 1.8 - 4.6	4.35	61.0%
Penetration	Average 67.19 Range 1.8 - 762.4	Average 2.89 Range 2.1 - 4.9	64.30	95.7%
Low level	Average 128.27 Range 1.8 - 622.1	Average 3.03 Range 1.8 - 6.6	125.24	97.6%

11.416 Comparison of Voice and Tone Warning Signals

Table 1. Individual subject data. (From Ref. 3)

Test Situation	Type of Warning	Subject	Scanned Master Caution Light	Scanned Annunciator Panel	Scanned Fail Switches	Failure Corrected	Remarks
High Task Loading and Saturation (Failure Point 2)	Tone	1	Yes	Yes	No	Yes	
	Tone	4	Yes	Yes	No	Yes	
	Tone	5	Yes	Yes	Yes	Yes	Incorrect sequence
	Voice	2	Yes	No	No	No	Did not correct—ignored failure
	Voice	3	No	No	Yes	Yes	Corrected failure—incorrect sequence
	Voice	6	Yes	No	No	No	Corrected Master Caution Light only—ignored failure
	Voice	7	No	No	Yes	Yes	Looked to hydraulic switches, then failure
	Voice	8	Yes	No	Yes	Yes	
	Voice	9	No	No	Yes	Yes	
	Voice	10	No	No	Yes	Yes	
	Voice	11	No	No	No	Yes	
	Voice	12	Yes	No	No	Yes	
Low Task Loading and Low Saturation (Failure Point 1)	Tone	1	Yes	Yes	No	Yes	
	Tone	4	Yes	Yes	No	Yes	
	Tone	5	Yes	Yes	Yes	Yes	
	Voice	2	Yes	No	No	Yes	
	Voice	3	Yes	No	Yes	Yes	
	Voice	6	No	No	Yes	Yes	Corrected Master Caution Light last
	Voice	7	No	No	No	Yes	
	Voice	8	Yes	Yes	Yes	Yes	
	Voice	9	Yes	No	Yes	Yes	
	Voice	10	No	No	No	Yes	
	Voice	11	Yes	No	No	Yes	
	Voice	12	Yes	No	Yes	Yes	Corrected Master Caution Light last

Key Terms

Alerting systems; attentional directors; auditory warnings; voice signals; warning signals; warnings

General Description

Tone warnings require the operator to refer to the legend of a supplementary light signal (an annunciator panel) or to memorize tone meaning for event identification. In contrast, voice warnings provide explicit information about problems; response times to most voice warnings are faster than response times to tone warnings. In addition, pilots prefer the voice warning system.

Methods

Test Conditions

- F-111A flight simulator with head-up display (barometric altitude commands) and three degrees of motion; flight was 100-nautical-mile bombing mission; simulation included audio tapes of noise and communications for actual combat sorties and some simulated flak; head-up display disappeared at 1600 ft during climb-out
- A Thompson-Houston 7.6 cm orthicon high-resolution camera modified to a 1029-line black and white system transferred images from a modified Link SMK-23 moving map model of mountainous terrain to standard Conrac Model CQM-13/N 1000-line monitor mounted in pilot's windscreen; two back-to-back single convex collimating lenses (focal length of 203 cm) made image appear as terrain from flight altitude
- Non-critical emergency (warning was FWD EQUIP HOT) occurred late in bomb run (high task loading; Mission 1), or early while still in friendly territory (low task loading; Mission 2), or during climb-out after attention was back in cockpit (in-cockpit baseline; Mission 3)
- Master caution light located directly on top center of instrument panel
- Female verbal warning message; warning message lasted ~3 sec, with 2 sec between messages; tone warning signal was 1250-3000-Hz sweeping tone with 500-msec sweep duration; all auditory warnings presented via earphones at ~10 dB louder than other transmissions
- Verbal messages repeated until pilot depressed master light or took proper action; annunciator light (located bottom center of instrument panel) extinguished only when pilot took proper action
- Pilot's eye-scan and head movements recorded by MTI Model VC-21 vidicon camera, beginning 10 sec before emergency; separate audio track on same video tape recorded voice warnings
- Each pilot practiced in the simulator until proficient at handling three emergencies, including the experimental emergency
- Questionnaire data collected during debriefing after experiment

Experimental Procedure

- Between-subjects unbalanced design
- Independent variable: failure condition
- Dependent variables: response time; subject's eye-scan pattern of master caution light, individual caution lights, and response switches; correction or non-correc-

tion of emergency/failure
- Subject's task: terminate warning signal by depressing master light or correct failure while performing mission tasks
- 12 male pilots (11 Air Force and 1 Navy), with an average of 3267 hours of flying time; 10 of the 12 averaged 322 hours of combat flying; 11 of the 12 were current in high-performance jet aircraft

Experimental Results

- Subjects consistently perform better with the voice warning system than with the tone warning system; differences in mean response times range from 0.98-2.40 sec.
- Subjects hearing a verbal warning do not automatically scan an annunciator panel when correcting a problem, but all subjects hearing tone warnings scan the annunciator panel.
- The benefits of voice warning are more apparent under high task loading.
- Most subjects generally favor the voice warning system, but many also want a back-up annunciator panel (from questionnaire data).

Variability

Analysis of variance was used to compare performance within the voice group under different task load conditions. However, no information on variability was given.

Repeatability/Comparison with Other Studies

Responding to a similar questionnaire, 91 of 97 B-58 pilots felt that the verbal warning signal contributed to flight safety. Ninety-five of the 97 preferred the voice warning system for the new F-111 aircraft. Other studies (e.g., Ref. 6) have found that identification of a critical event is faster for verbal auditory warning signals than for non-verbal warning signals (e.g., a buzzer) across different primary task difficulties. Also, the verbal warning signal provided the least interference with the primary task (concurrent visual-motor tracking).

Constraints

- Both the point of failure in the mission and the degree of task loading were perfectly correlated with the mission stage (e.g., Mission 2 failure was always at an early point in the mission and was during a period of low task loading).
- Formal statistical comparison of the tone and voice warning groups was not done because there were only three subjects in the tone group.

Key References

1. Directorate of Aerospace Safety. (1967, July). *Consolidation of B-58 voice warning system (VWS) crew questionnaire*. Norton AFB, CA.

2. Headquarters, Tactical Air Command, USAF. (1963 June). *Operational test and evaluation: Verbal warning system* (TAC-TR-62-20). Langley AFB, VA: Tactical Air Command. (DTIC No. AD16258)

*3. Kemmerling, P., Geiselhart, R., Thornburn, D. E., & Cronburg, J. G. (1969 September). *A comparison of voice and tone warning systems as a function of task loading* (ASD-TR-69-104). Wright-Patterson AFB, OH: Aeronautical Systems Division. (DTIC AD 702459)

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5. Pollack, I., & Tecce, J. (1958). Speech annunciator warning indicator system: Preliminary evaluation. *Journal of the Acoustical Society of America, 30*, 58-62.

6. Simpson, C. A., & Williams, D. H. (1980). Response time effects of alerting tone and semantic context for synthesized voice cockpit warnings. *Human Factors*, 22, 319-330.

7. Wheale, J. (1982 July). Performance decrements associated with reaction to voice warning messages. *Proceedings of the AGARD Conference on Advanced Avionics and the Military Aircraft Man/Machine Interface* (pp. 18-1 - 18-2). (AGARD-CP-329)

Cross References

2.801 Sound localization;

2.816 Localization in noise;

11.415 Coupling of visual and verbal warning signals: effect on response time;

11.418 Voice warning systems: effect of message structure and content

Table 2. Mean response time to failures (in seconds). (From Ref. 3)

Type of Warning	Failure I	Failure II	Failure III
Tone	8.99 (N = 3)	8.93 (N = 3)	10.13 (N = 3)
Voice	8.01 (N = 9)	6.53 (N = 7)	9.13 (N = 9)

11.417 Voice Auditory Warning Signals: Effect of Alerting Tones

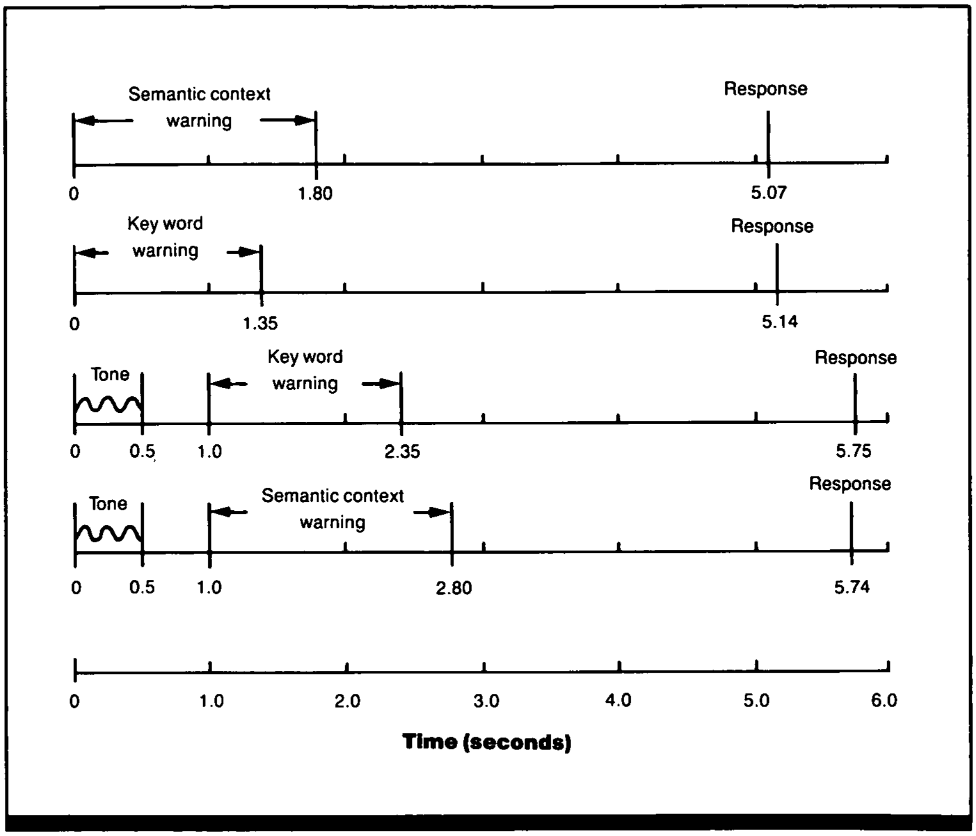

Figure 1. Mean response times, in seconds, for four warning message conditions. (From Ref. 2)

Key Terms

Keyword cueing; non-verbal auditory signals; semantic context; synthesized voice warnings; verbal signals; voice signals; warnings

General Description

Response times to a semantic (contracted sentence) version and a shorter keyword version of a voice warning message are about equal. A tone preceding either version significantly increases the total time for response (from event occurrence, i.e., start of tone, to correct response).

Methods

Test Conditions

- Primary task was flying S-21 fixed-base simulator programmed with simplified flight dynamics of Boeing 727; cockpit communications with standard air traffic control, including two other simulators and many computer-generated aircraft; some cockpit conversation; light visual workload, because no visual simulation of external scene or other aircraft
- Verbal warnings presented via VOTRAX VS-6 voice synthesizer were either contracted sentences (semantic condition) or keywords only
- Two warning context conditions (keyword, semanic) were crossed with two tone conditions (no tone, tone); tone condition consisted of verbal warning preceded by 500 msec, 1000 Hz tone with 500 msec interstimulus-interval between tone offset and verbal warning onset (Fig. 1); tone occurred only once per warning; message repeated until action was taken
- PDP-12 drove the voice synthesizer and controlled random presentation of different warning signals
- 12-function response box (4 × 3 button array) located behind and below seatpan position of subject; each of six warnings had one correct, unambiguous response; other six cockpit box buttons would cancel the ongoing error and be scored by the computer as an error; warnings and responses from current jet transport operating manual
- Cockpit noise was simulated aircraft noise produced by Conduction Sound Simulation System, Model 68H006; averaged 75 dB (re 0.00002 N/m^2); conversations were 78 ±5 dB SPL; air traffic control communications averaged ~79 ±4 dB SPL; verbal warnings at 76 ± 1 dB SPL; tone at 89 dB SPL; all measurements taken 12 cm from the side of pilot's right ear

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Procedure

- Within-subjects design
- Independent variables: warning message, context of message, presence or absence of warning tone
- Dependent variable: response time
- Subject's task: respond to warning by depressing appropriate button on response box
- 4 subjects were commercial-airline pilots, completely trained on correct responses two weeks before test flight and with preflight warning-equipment check

Experimental Results

- Presence of tone, with voice warning delayed by 1 sec from start of event, significantly ($p < 0.05$) lengthened response time; no other factors were significant.
- Making the verbal warning longer by including more words in the semantic condition did not increase response time.

Variability

Response-time variations were ± 0.70 and ± 0.88 sec for keyword messages with and without tone, respectively, and ± 0.63 and ± 0.73 sec for semantic messages with and without tone, respectively.

Constraints

- Data refer to commercial aircraft with associated air traffic control and other auditory inputs. Military aircraft auditory inputs will differ, but general conclusion will probably be the same.
- The with-tone conditions delayed start of the voice warning by 1 sec. With a 1/8 sec tone and no delay between tone end and voice, the tone might have been of value. Results of study are for a 1-sec delay between time zero and start of voice with the tone condition.

Key References

1. Kemmerling, P., Geiselhart, R., Thorburn, D. E., & Cronburg, J. G. (1969, September). *A comparison of voice and tone warning systems as a function of task loading* (ASD-TR-69-104). Wright-Patterson Air Force Base, OH: Air Force Systems Command, Aeronautical Systems Division, Deputy for Engineering. (DTIC No. AD702459)

*2. Simpson, C. A., & Williams, D. H. (1980). Response time effects of alerting tone and semantic context for synthesized voice cockpit warnings. *Human Factors, 22*(3), 319-330.

Cross References

2.801 Sound localization;

2.816 Localization in noise;

8.305 Noise masking of speech: effect of signal-to-noise ratio;

11.336 Guidelines for the use of noncritical auditory signals;

11.415 Coupling of visual and verbal warning signals: effect on response time;

11.416 Comparison of voice and tone warning signals

11.418 Voice Warning Systems: Effect of Message Structure and Content

Table 1. Index of confusion for single-engine messages. (From Ref. 1)

Unique First Word		Military Specification	
Message	**Average Ranking**	**Message**	**Average Ranking**
Fire engine	0.785	Engine fuel pumps	1.241
N_1 high	0.776	Engine rpm high	1.080
EGT low	0.745	Engine rmp low	1.785
Rotor rpm high	0.696	Engine oil	0.589
Rotor rpm low	0.669	Hydraulic one and two pressure	0.562
Low transmission pressure	0.650	Fuel quality low	0.535
Rotor chip	0.638	Transmission oil temperature	0.464
EGT high	0.625	Engine chip	0.401
Double hydraulic pressure	0.571	Fuel boost forward and aft	0.339
Hydraulic pressure	0.526	Fuel contaminated	0.339
Chip engine	0.516	Engine fire	0.312
Fuselage fire	0.513	Tail rotor chip	0.267
Tail rotor	0.508	Transmission oil pressure	0.089
Oil (pressure)	0.491	SAS	0
Transmission chip	0.433	Fuel boost (pump)	0
Electric fire	0.419	Total	7.003
Hot transmission oil	0.401	Average	0.466
Low fuel quantity	0.375		
Fuel control	0.334		
Generator	0.316		
Inverter	0.303		
N_1 low	0.272		
Contaminated fuel	0.245		
Double boost	0.191		
Boost (pump)	0.187		
External power (connected)	0.133		
Check caution panel	0.089		
Ice	0.080		
Total	12.487		
Average	0.445		

Key Terms

Alerting systems; auditory warnings; cautions; information transfer; message content; message structure; verbal warnings; voice synthesis; voice warnings; warnings

General Description

A comparison of voice warnings that conform to MIL-STD-411 requirements and voice warnings with unique first words addressed three main problems: (1) the identification and selection of messages for maximum effectiveness; (2) the determination of priority sequences; and (3) the integration of the Voice Warning System (VWS) into existing cockpits. Tables 1 and 2 list the confusability rankings for both types of messages; general recommendations are listed in the Experimental Results section.

General Methodology

- Information requirements analyses of missions and emergencies for six Army aircraft; task analysis for each emergency determined preliminary priority sequencing of emergency messages
- Accident statistics reviewed to contribute to message prioritization and VWS effectiveness
- Pilot-opinion surveys (180 subjects) to verify validity of preliminary message content and priority sequencing
- Cockpit-integration analyses examined message redundancy and considered VWS in association with high-noise environment
- Message content analysis included word discrimination tests for message development and subsequent testing of the lists
- Subject's task: rank each message on a scale of 0-10, with higher numbers indicating increased confusion
- 8 subjects, pilot-engineers

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Average rank of confusion for the two lists of verbal warnings (experimentally proposed and MIL-STD-411D) are similar for single-engine planes, but engine-related warnings using military specification terms are judged more confusable (i.e., have higher confusion rankings).
- Average rank of confusion for messages for multi-engine planes is much higher for messages conforming to military standards.
- There is greater confusion for more military specification phrases; unique first words and variation in order of words yield lower confusion indices than warnings conforming to military specifications.
- Similarity of words or similarity of endings or beginnings of words contributes to greater confusion. Similarity of words in a set is more prevalent in the military specification messages because system, subsystem, and failure must be identified in that order for each message.
- Prioritization of warning messages is dependent upon the task requirements in response to failure and the mission and safety threat. Prioritization is specific to each system.
- Recommendations to remove visual displays on integration of the VWS may be made only if there is complete informational overlap and there is no benefit from the redundancy.
- Results indicate that an alerting signal preceding a message to ensure full attention to the message may be beneficial in noisy environments.
- The noise level in current cockpits may prevent hearing voice warnings, at least part of the time. Consequently, voice warnings should be integrated with visual warnings, rather than replacing them. Also, acceptable signal-to-noise ratios should be determined for a variety of different circumstances (e.g., full-throttle operation versus no engines).

Variability

Analytical study with minimal empirical components.

Constraints

- Only one female voice was used for the messages in the study; voice quality, clarity, and ability to be understood should be further studied to evaluate the VWS.
- An alerting tone prior to a message was not used; further study is required to evaluate the use of a tone in reducing confusion factors.

Key References

*1. Brown, J. E., Bertone, C. M., & Obermayer, R. W. (1968, February). *Army aircraft voice-warning system study* (HEL-TM-6-68). Aberdeen Proving Ground, MD: U.S. Army Human Engineering Labs. (DTIC No. AD667924)

2. Department of Defense (DoD). (1970). *Military standard. Air crew station signals* (MIL-STD-411D). Washington, DC: DoD.

3. Licklider, J. C. R. (1961, March). *Audio warning signals for Air Force weapon systems*, WADC-TR-60-814. Wright-Patterson Air Force Base, OH: Wright Air Development Center. (DTIC No. AD258530)

Cross References

8.304 Factors affecting the intelligibility of speech in noise;

8.308 Noise masking of speech: effect of word usage frequency and word length

Table 2. Index of confusion for multi-engine messages. (From Ref. 1)

Unique First Word		Military Specification	
Message	Average Ranking	Message	Average Ranking
N_1 high engine two	1.400	Engine two rpm high	1.821
EGT two high	1.185	EGT two low	1.685
N_1 high engine one	1.150	Engine two rpm low	1.571
N_1 low engine two	0.914	EGT two high	1.557
Chips engine two	0.885	EGT one low	1.364
EGT two low	0.878	Engine one rpm high	1.350
Fire engine two	0.771	Engine two oil	1.242
EGT one high	0.735	EGT one high	1.150
N_1 low engine one	0.685	Engine one rpm low	1.071
Chips engine one	0.600	Engine one oil	0.971
EGT one low	0.500	Engine two chip	0.942
Fire engine one	0.407	Engine two fire	0.942
Left-wing fire	0.371	Right-wing fire	0.742
Engine two failure	0.300	Left-wing fire	0.707
Both engines	0.200	Engine one chip	0.678
Right-wing fire	0.128	Engine one fire	0.657
AFCS	0.107	Engine one and two failure	0.450
Intermediate transmission pressure	0.021	Fuel control two	0.392
		Engine two failure	0.250
Oil (quantity)	0.014	Fuel control one	0.157
Ice	0	Total	19.699
Total	11.251	Average	0.984
Average	0.562		

11.419 Coupling of Visual and Aural Warning Signals: Effect on Eye Fixation and Response Time

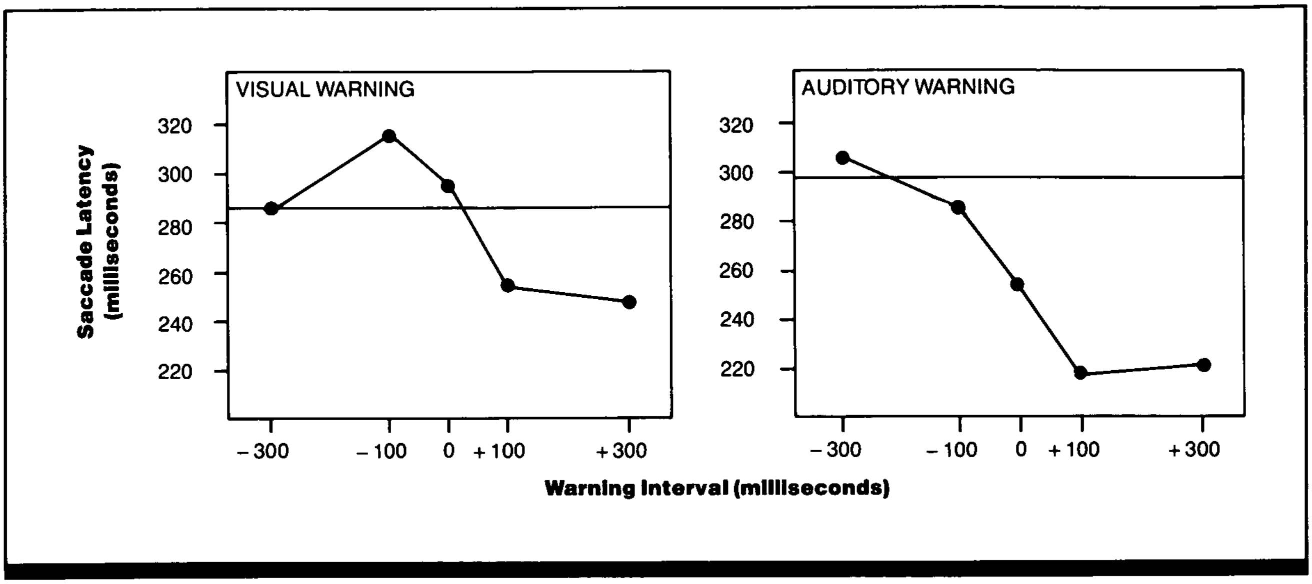

Figure 1. Mean saccade latency as a function of warning interval for visual and auditory warning-signal conditions. The mean no-warning latencies are represented by the horizontal lines. A negative warning interval indicates the warning-signal onset occurred after the target-signal onset. (From Ref. 2)

Key Terms

Afterimaging; auditory warnings; saccadic eye movement; saccadic latency; visual fixation; warnings

General Description

When a foveal warning-signal onset occurs within ~100 msec *after* a peripheral target-signal onset, the onset of the eye movement (saccade) to fixate the target is delayed (i.e., saccade latency or delay is greater than when no warning signal occurs). This interference does not occur if the warning signal is auditory rather than visual (Fig. 1). The interference is limited to eye-movement responses and does not apply to hand movements (e.g., moving a lever in response to the visual target signal in Fig. 2). If the warning signal occurs in the peripheral rather than the foveal visual field (e.g., 5.5 deg from fixation), interference also occurs when the onsets of the visual warning and target signals are simultaneous.

In contrast, if a visual or auditory warning signal onset occurs 100-300 msec *before* the target onset, eye movement to target is faster than when no warning signal is presented. A simultaneous auditory warning-signal onset will also decrease eye-movement latencies (Fig. 1). A similar facilitation for hand movements occurs when a visual warning signal is presented 0, 100, or 300 msec before onset of a target requiring a hand-movement response.

Applications

Design of alert systems; eye-response (oculomotor) information is helpful when specifying the characteristics of light sources to provide for maximum detection probability and response speed.

Methods

Test Conditions

- Subject sat in an ophthalmologist's chair with adjustable head rest and viewed a display screen at 60-cm distance through a 2.5 × 36.5 cm slot (Exps. 1, 2) or a 35.5 × 15.3 cm slot (Exp. 3) in a black panel
- 45 dBA white-noise background continuously presented through a loudspeaker above display
- Room was dark except for single 15W incandescent bulb behind panel
- Subject eye movements recorded by a NARCO Biometric Eye Trac Model 200 eye tracker (horizontal from right eye, vertical from left eye) to determine saccade onset and latencies
- Target was an "X" (0.5 deg arc of visual angle vertically and 0.35 deg horizontally) at 15 deg to right or left of eye fixation point
- "O" presented foveally as visual warning symbol (Exps. 1, 2) or two Os were presented 5.5 deg above, below, to right, or to left of eye fixation point (Exp. 3); auditory warning signal was a 1000-Hz, 70-dB tone
- Six warning signal interval conditions: no warning, −300, −100, 0, 100, 300 msec
- Conditions randomly assigned in blocks

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Procedure

- Mixed, randomized block design
- Independent variables: warning signal type, warning-signal interval, foveal or peripheral warning signal
- Dependent variables: eye-movement latency, manual-response latency (reaction time)
- Subject's task: look at target X as quickly as possible, or respond to it by pulling lever to side where X appeared
- Eye sensors calibrated pretest and checked prior to each trial
- 16 male and 16 female college students with 20/20 uncorrected near vision (Exps. 1, 3); 8 male and 8 female college students (Exp. 2)

Experimental Results

- Eye-movements (saccades) to fixate targets are facilitated by presentation of either a visual or auditory warning signal 100-300 msec before the visual target signal.
- A peripheral visual warning signal that occurs simultaneously with the visual target signal will increase saccade latency (slow the response), whereas a simultaneous auditory warning signal will decrease saccade latency (quicken response).
- A visual warning signal that occurs ~100 msec after the visual target signal also slows the response; there is no effect for an auditory signal that occurs after the target signal.
- Hand-movement responses occur more quickly (Fig. 2) when a visual warning signal is presented 0, 100, or 300 msec before the target signal requiring the hand response (when compared to times when no warning signal is presented). There is no interference with hand movements if the visual warning signal is presented after the target signal.

Variability

Analysis of variance and *t* tests were conducted.

Constraints

- Only one warning was presented each trial; results may vary with more than one warning signal.
- Only one primary task was required; subject was watching for target X. Results may vary for different workloads and for non-visual additional tasks.
- In real systems there is frequently no way for the system to be aware of a target before it appears on the display, i.e., to give the operator a warning signal in advance of appearance on the display.

Key References

1. Ross, L. E., & Ross, S. M. (1980). Saccade latency and warning signals: Stimulus onset, offset, and change as warning events. *Perception & Psychophysics, 27,* 251-257.

*2. Ross, S. M., & Ross, L. E. (1981). Saccade latency and warning signals: Effects of auditory and visual stimulus onset and offset. *Perception & Psychophysics, 29,* 429-437.

Cross References

2.815 Effect of visual and proprioceptive cues on localization;

11.405 Visual warning signals: effect of visual field position and color;

11.408 Master warning signals: effect on detection of signals in the visual periphery;

11.409 Visual warning signals: effect of size and location;

11.413 Coupling of visual and auditory warning signals: effects on detection and recognition;

11.415 Coupling of visual and verbal warning signals: effect on response time;

11.421 Integration of visual and auditory alerts in warning systems

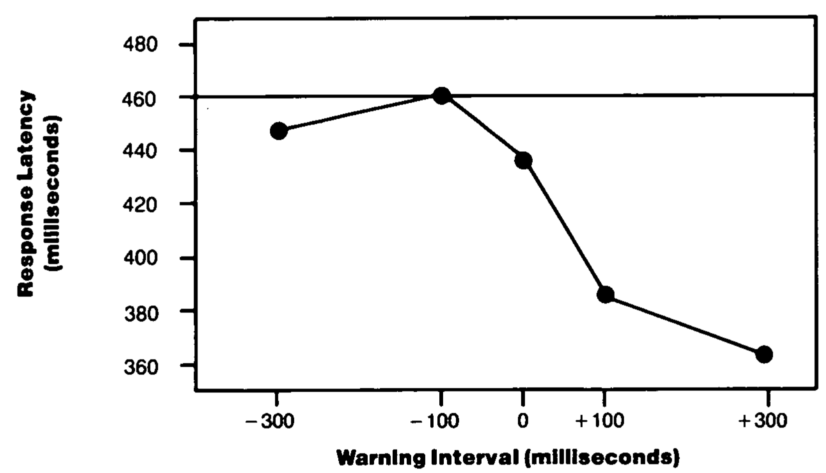

Figure 2. Mean manual-response latency as a function of warning interval. The mean no-warning latency is represented by the horizontal line. A negative warning interval indicates the warning-signal onset occurred after the target-signal onset. (From Ref. 2)

11.420 Response Time with Redundant Information

Table 1. Effects of redundancy on reaction time.

Nature of Redundancy	Task Description	Effect	Source
One modality, different codes	36 cards to be sorted by number into six piles; each card contained either: 1. single digit (e.g., 6) 2. several Xs (e.g., 6 Xs) 3. several digits (e.g., six 6s)	Sorting time is shorter with redundant information (37 sec) than with no redundancy (39 sec)	Ref. 5
	Brightness and size paired on card sorting task	Small facilitation	Ref. 1
	Seven card-sorting experiments with 32 cards sorted into two piles. Stimulus dimensions were value and chroma for single Munsell color chips, value and chroma each on separate Munsell chips, horizontal and vertical positions of dots, size of circles and angles of diameters drawn through circles, and these same pairings with greater differences within dimensions to increase discriminability	There are no redundancy effects when the redundant information comes from two separate objects (e.g., two color chips on one card) There are two types of dimensions: integral dimensions are processed as holistic unit (e.g., value and chroma), separable dimensions are processed individually (e.g., size and angle). For integral dimensions, redundancy facilitates performance and orthogonal dimensions slow performance (i.e., sorting time). Increasing discriminability can slightly improve performance, but high discriminability can also limit the sensitivity of an experiment to the effects of redundant and orthogonal dimensions	Ref. 2
Two modalities	Both auditory and visual stimuli versus either modality alone	Considerable increase in correct detections with redundant information	CRef. 7.409
	Pairings of sound and shock, and light and sound	Facilitation only for pairings of sound and shock	Ref. 5
	Variable stimulus-onset interval for auditory stimulus following a visual stimulus	Facilitation only when stimulus-onset interval was 30-50 msec	CRef. 9.114
	Visual signal preceding a proprioceptive signal	Facilitation occurs	Ref. 4
	Detection of temporal patterns of left-right sequences for visual, auditory, and touch stimuli in all possible combinations (e.g., visual, auditory, and touch)	Only effect is a facilitation for visual and auditory at a fast (four elements per sec) rate of presentation	CRef. 5.1018

Key Terms

Expectancy; intersensory stimulation; reaction time; redundant cues; simulation fidelity; vigilance; warnings

General Description

Redundant information is present when there is more than one source of the same information. Redundant information can occur in several ways: there may be repeated signals (e.g., identical warning signs on both sides of a highway); the signals may be in different codes (e.g., colors and words on a highway sign); or the signals may be in different sensory modalities (e.g., simultaneous visual and auditory warning signals).

The presence of redundant information decreases reaction time (RT). The table describes several types of redundancy and their effects on performance. The facilitation may be very slight or fairly large, depending on the task and the performance measures.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Shorter RT is often associated with higher error rate (CRef. 9.114).
- The Hick-Hyman law of choice reaction time (RT) is $RT = a + bH_S = a + bH_T$, where H_S is the amount of information (number of bits) in the stimuli and H_T is the amount of information transmitted. Under ideal choice RT conditions in which an observer always responds with the single response associated with each stimulus, $H_S = H_T = \log_2 N$, where N equals the number of alternative stimulus-response pairs. However, this equality does not hold when conditions are not ideal. Then, RT is more accurately a function of the amount of transmitted information, rather than the number of alternative stimulus-response pairs. For details on the computation of H_T in this type of situation, see Ref. 3.

Key References

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5. Morton, J. (1969). The use of correlated stimulus information in card sorting. *Perception & Psychophysics, 5*, 374-376.

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Cross References

5.1018 Temporal pattern recognition with unimodal versus multimodal presentation;

7.409 Simultaneous versus independent visual and auditory monitoring;

9.114 Choice reaction time: effect of warning interval on error

11.421 Integration of Visual and Auditory Alerts in Warning Systems

Key Terms

Alerting systems; cautions; voice warnings; warnings

General Description

Based on a considerable amount of experimentally derived data and a preponderance of pilot recommendations resulting from experience with different types of alerting techniques, logic is an essential component to ensuring appropriate alert presentation format for each alert criticality level (see Table 1). The following are additional guidelines for optional alert integration:

- Onset of master visual alert should coincide with onset of master aural alert.
- Voice message should be direct verbal extensions of the legend message on information display.
- Master alerts and voice information display should cancel automatically on fault correction or by pilot action and, depending on event criticality, be time-duration limited.
- Visual messages on information displays should be stored by alerting system computer for post-flight maintenance analysis.
- All alerts should be prioritized and, when visual, grouped in priority arrangement.
- Time-critical warning should inhibit real time presentation of other warnings, unless of equal urgency, until time-critical situation rectified or pilot overrides alerting mechanism.

Constraints

- The proposed alerting system integration is a guideline; implementation and verification of the effectiveness of the recommendations are necessary.

Key References

*1. Berson, B. L., Po-Chedley, D. A., Boucek, G. P., Hanson, D. C., Leffler, M. F., & Wasson, R. L. (1981, January). *Aircraft alerting system standardization study: Vol. II. Aircraft alerting system design guidelines* (FAA/RD-81-38-2) Seattle, WA: Boeing Commercial Airplane Co. (DTIC No. ADA106732).

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Cross References

2.815 Effect of visual and proprioceptive cues on localization;

11.402 Alarm classification and development;

11.415 Couling of visual and verbal warning signals: effect on response time;

11.416 Comparison of voice and tone warning signals;

11.417 Voice auditory warning signals: effect of alerting tones;

11.419 Coupling of visual and aural warning signals: effect on eye fixation and response time

Table 1. Alerting system integration for single and multiple alerts. (From Ref. 1)

	Alerting system components												
Event	Master Visual		Visual Information Display	Time Critical Display	Master Aural			Verbal Message		Cancelation		Comments
	Warning	Caution			Warning	Caution	Advisory	Elective	Mandatory	Master Visual	Control Wheel Switch	
0. No alerts												No system response
1. Single advisory			X				X					In all cases where advisory-level alerts occur, the corresponding master aural sounds once then cancels automatically
2. Single caution		X	X			X		X		X	X	See Note 1: master aural sounds once, and repeats at 10-sec intervals if no action taken
3. Single warning	X		X		X			X		X	X	See Note 1: master aural continues until manually canceled by either method described in Note 1
4. Single time-critical warning	X		X	X	X				X	X		See Notes 1 and 2: guidance information presented in both graphics and alphanumerics on the time-critical display
5. One advisory and one caution		X	Both messages displayed			X	X	X		X	X	See Notes 1, 3, and 4
6. One advisory and one warning	X		Both messages dislayed		X		X	X		X	X	See Notes 1, 3, and 4
7. One advisory and one time-critical warning	X		Both messages displayed	Only time-critical alert displayed	X				X	X		See Notes 2, 3, and 5
8. One or more cautions and one warning	X	X	All messages displayed		X	X		X		X	X	See Notes 1, 3, and 4. If control wheel switch is depressed, only the voice warning is presented
9. One or more cautions and one time-critical warning			All messages displayed	Only time-critical alert displayed	X				X	X		See Notes 2, 3, and 5
10. One or more warnings and one time-critical warning	X		All messages displayed	Only time-critical alert displayed	X				X	X		See Notes 2, 3, and 5
11. Two or more advisories			All messages displayed				X					See Note 3
12. Two or more cautions		X	All messages displayed			X		X		X	X	See Notes 1 and 3. Depression of control wheel switch will activate the voice message "multiple alert"
13. Two or more warnings	X		All messages displayed		X			X		X	X	See Notes 1 and 3. Depression of control wheel switch will activate the voice message "multiple alerts."
14. Two or more time-critical warnings	X		All messages displayed	All time-critical messages in succession	X				X	X		Master aural followed by alternating repetitions of each voice message, which will correspond to visual messages presented on time-critical display. See Notes 2, 3, and 5.
15. One or more advisory and two or more cautions		X	All messages displayed			X	X	X		X	X	See Notes 1 and 3. Depression of control wheel switch will activate the voice message "multiple alerts."
16. One or more advisories and two or more warnings	X		All messages displayed		X		X	X		X	X	See Notes 1 and 3. Depression of control wheel switch will activate the voice message "multiple alerts."

(Continued)

Table 1. *(Continued)*

Event	Alerting system components											Comments
	Master Visual		Central Information Display	Time Critical Display	Master Aural			Verbal Message		Cancelation		
	Warning	Caution			Warning	Caution	Advisory	Elective	Mandatory	Master Visual	Control Wheel Switch	
17. One or more advisories and two or more time-critical warnings	X		All messages displayed	All time-critical messages in succession	X				X	X		Master aural followed by alternating repetitions of each voice message, which will correspond to visual messages presented on time-critical display. See Notes 2, 3, and 5.
18. One or more cautions and two or more warnings	X	X	All messages displayed		X	X		X		X	X	See Notes 1 and 3. Depression of control wheel switch will activate the voice message "multiple alerts."
19. One or more cautions and two or more time-critical warnings	X		All messages displayed	All time-critical messages in succession	X				X	X		Master aural followed by alternating repetitions of each voice message which will correspond to visual messages presented on time-critical display. See Notes 2, 3, and 5.
20. One or more warnings and two or more time-critical warnings	X		All messages displayed	All time-critical messages in succession	X				X	X		Master aural followed by alternating repetitions of each voice message, which will correspond to visual messages presented on time-critical display. See Notes 2, 3, and 5.
21. One or more advisories, one or more cautions, and one warning	X	X	All messages displayed		X	X	X	X		X	X	See Notes 1, 3, and 4. If control wheel switch is depressed, only the voice message for the warning is presented.
22. One or more cautions, one or more warnings, and one time-critical warning	X		All messages displayed	All time-critical messages in succession	X				X	X		Master aural followed by alternating repetitions of each voice message, which will correspond to visual messages presented on time-critical display. See Notes 2, 3, and 5.
23. One or more advisories, one or more cautions, and two or more warnings	X	X	All messages displayed		X	X	X	X		X	X	See Notes 1 and 3. Depression of control wheel switch will activate the voice message "multiple aleris."
24. One or more cautions, one or more warnings, and two time-critical warnings.	X			All time-critical messages in succession	X				X	X		Master aural followed by alternating repetitions of each voice message, which will correspond to visual messages presented on time-critical display. See Notes 2, 3, and 5.

Notes:

1. Master aural and visual alerts can be canceled by either depressing the master visual light switch or by actuating the control wheel switch to present the voice message.

2. Time-critical voice messages can be canceled after one iteration by depressing the master visual light. Regardless of when the master visual light is depressed, the voice message will be annunciated at least once.

3. Simultaneous alerts are defined as two or more alerts occurring before any overt physical action is taken by the crew (for example, manual cancellation of the master visual and aural alerts).

4. Depressing the control wheel switch will activate a voice message for the most recent warning or caution-level alert.

5. The occurrence of time-critical warnings will cause the automatic inhibition of all components of lower priority alerts until the pilot manually cancels the voice alert message or corrects the problem (except for the visual information display).

Key Terms

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Glossary

Binocular disparity. *See* **lateral retinal image disparity.**

Compensatory tracking. Tracking in which the operator's display shows only the direction and magnitude of tracking error and does not independently present the command input and system position. The task is to compensate (correct) error.

Contrast sensitivity. The ability to perceive a lightness or brightness difference between two areas; generally measured as the reciprocal of the contrast threshold. Contrast sensitivity is frequently measured for a range of target patterns differing in value along some dimension such as pattern element size and portrayed graphically in a **contrast sensitivity function** in which the reciprocal of contrast threshold is plotted against, e.g., pattern spatial frequency.

Frame. (1) In CRT displays, one complete scan of the image area by the electron beam. (2) In motion-picture film, a single image of the connected multiple images.

Lateral retinal image disparity. The difference in the relative horizontal position of the visual images of an object on the left and right retinas due to the lateral separation of the eyes. (CRef. 5.905)

Luminance. Luminous flux reflected or transmitted by a surface per unit solid angle per unit of projected area in a given direction. The most commonly used units of measurement are candelas per meter^2 (cd/m^2), footlamberts (fL), and millilamberts (mL). (CRef. 1.104)

Modulation transfer function. The function (usually graphic) describing the ratio of the modulation of the input to the modulation of the output over a range of frequencies; for an image-forming system, the ratio of the modulation in the image to that in the object. Also called **sine-wave response function** and **contrast transfer function.**

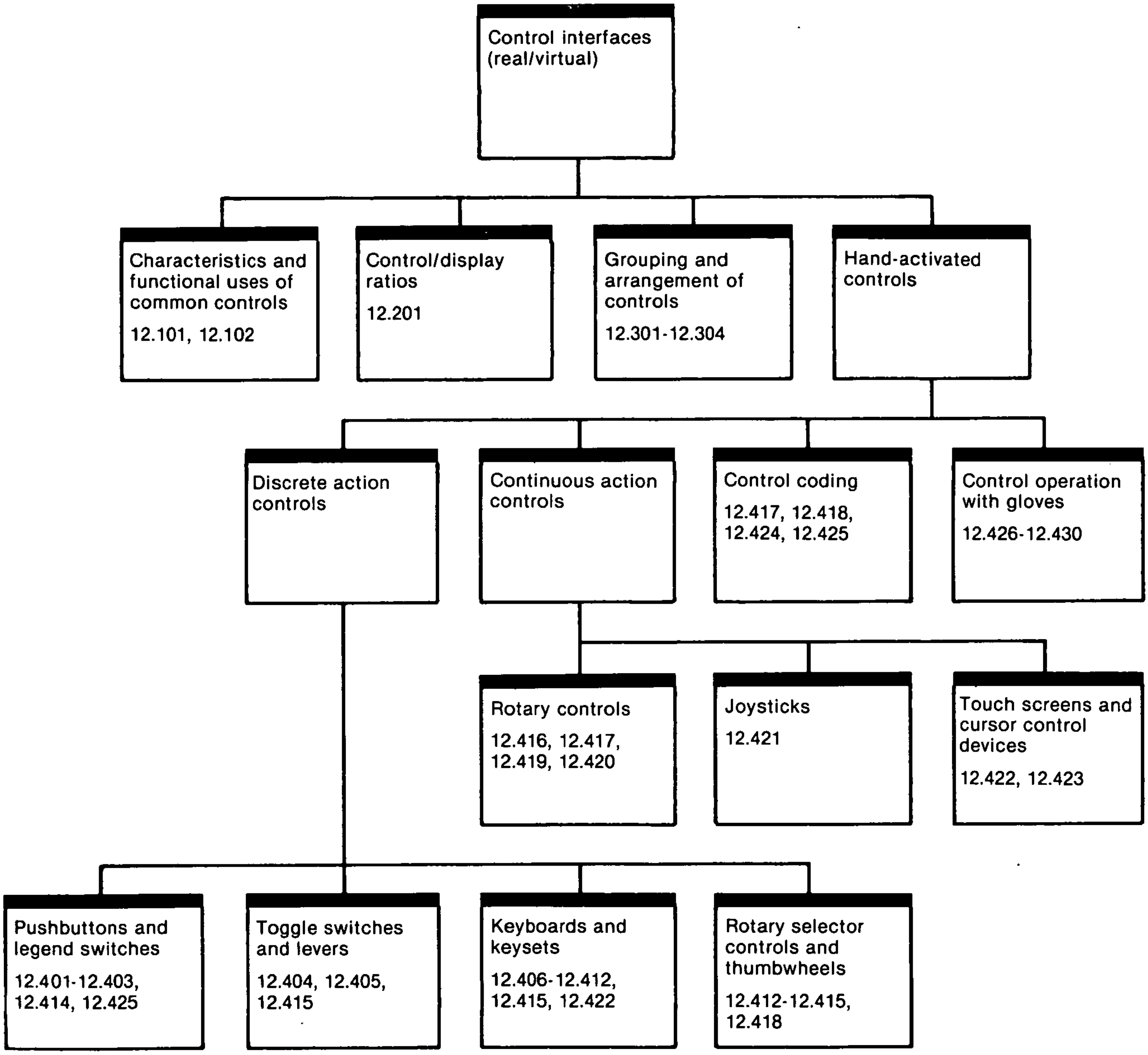
Motion parallax. Changes in the projective relations among objects in the visual field due to the relative motion of the observer. (CRef. 5.902)

Orthogonal. Completely independent or separable.

Reaction time. The time from the onset of a stimulus to the beginning of the subject's response to the stimulus by a simple motor act (such as a button press).

Schema. A nonconscious adjustment of the brain to the afferent impulses indicative of body posture that is a prerequisite of appropriate bodily movement and of spatial perception.

Organization of Entries



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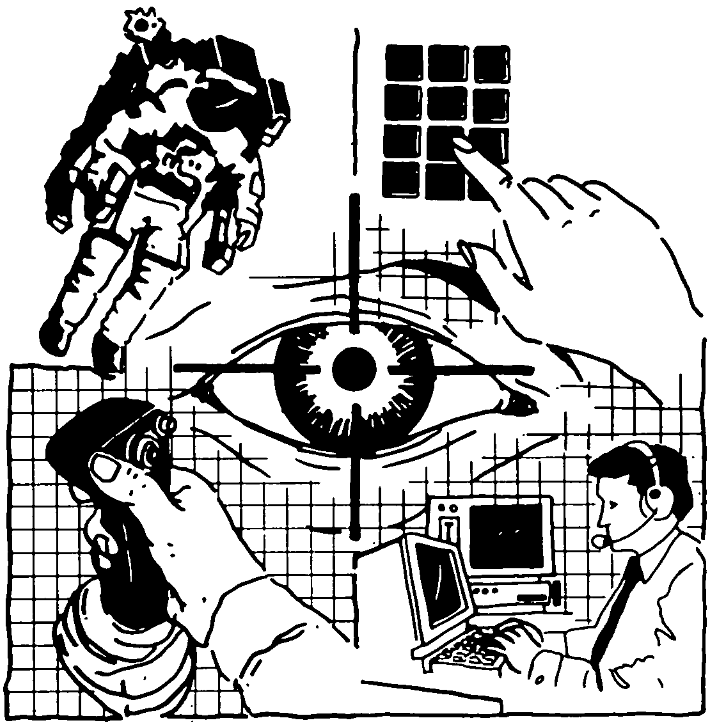
Section 12.0 Control Interfaces (Real/Virtual)



12.101 Recommended Uses of Controls

Table 1. Discrete controls. (Adapted from Ref. 1)

Type	Uses
Linear	
Pushbutton	Where a control or an array of controls is needed for momentary contact or for activating a locking circuit
Legend	Where an integral legend is required for pushbutton applications
Slide	Where two or more positions are required or are arranged in matrix to allow easy recognition of relative switch settings (e.g., auditory levels across channels)
Toggle	Where two positions are required or space limitations are severe Three-position toggles used only as spring-loaded center-off type or where rotary or legend controls are not feasible
Rocker	In place of toggles where toggles may cause snagging problems or where scarcity of panel space precludes separate labeling of switch positions Three-position rockers used only as spring-loaded center-off type or where rotary or legend controls are not feasible
Push-Pull	Where two positions are required and such configuration is expected (e.g., auto headlights, etc.) or where panel space is scarce and related functions can be combined (e.g., ON-OFF/volume control) Three-position push-pulls used only where inadvertent positioning is not critical
Rotary	
Selector	Where three or more positions are required In two-position applications where swift visual identification is more important than positioning speed
Key Operated	In two-position applications to prevent unauthorized operation
Thumbwheel	Where a compact digital control-input device with readout is required

Key Terms

Continuous controls; continuous rotary controls; discrete controls; ganged switches; isometric joystick; isotonic joystick; key-operated switches; legends; lever controls; light pens; mouse; push-pull switches; pushbuttons; rocker switches; selector switches; slide switches; thumbwheel switches; toggle switches; track balls

General Description

Table 1 lists discrete controls and recommended functional uses; Table 2 provides the same information for continuous controls. Each table is broken into linear and rotary types of control motion.

Constraints

- These recommendations are general in nature and may need to be modified for specific applications.

Key References

1. U.S. Army Missile Command (1981). *Human engineering design criteria for military systems, equipment and facilities* (MIL-STD-1472C). Philadelphia: Naval Publications and Forms Center.

2. U.S. Naval Air Systems Command (1973). *General requirements for aircraft control panel* (MIL-C-81774A). Philadelphia: Naval Publications and Forms Center.

Cross References

12.102 Comparison of common controls;

12.301 Principles of grouping and arranging controls

Table 2. Continuous controls. (Adapted from Ref. 1)

Type	Uses
Linear	
Lever	Where large amounts of force or displacement are involved or when multidimensional control movements are required
Isotonic (Displacement) Joystick	Where precise or continuous control in two or more related dimensions is required Where positioning accuracy is more important than positioning speed Data pickoff from CRT or free-drawn graphics
Isometric (Force) Joystick	Where a return to center after each entry or readout is required, operator feedback is primarily visual from system response rather than kinesthetic from the stick, and there is minimal delay and tight coupling between control and input and system response
Track Ball	Data pickoff from CRT Where there may be cumulative travel in a given direction Zero-order control only
Mouse	Data pickoff or entry of coordinate values on a CRT Zero-order control only
Light Pen	Track-oriented readout device Data pickoff, data entry on CRT
Rotary	
Continuous Rotary	Where low forces and precise adjustments of a continuous variable are required
Ganged	Used in limited applications where scarce panel space precludes the use of single continuous rotary controls
Thumbwheel	Used as an alternative to continuous rotary controls where a compact control device is required

12.102 Comparison of Common Controls

Table 1. Characteristics of common controls. (From Ref. 2)

	Control Type						
	Discrete				Continuous		
Characteristics	**Rotary Selector**	**Thumb-wheel**	**Push-button**	**Toggle Switch**	**Continuous Rotary**	**Thumb-wheel**	**Lever**
Space Requirement (Location and operation)	medium	small	small	small	small to medium	small	Medium to large
Likelihood of Accidental Activation	low	low	medium	medium	medium	high	high
Effectiveness of Coding	good	poor	fair to good	fair	good	poor	good
Ease of Visual Identification of Control Position	fair to good	good	poor[a]	fair to good	fair[b] to good	poor	fair to good
Ease of Non-Visual Identification of Control Position	fair to good	poor	fair	good	poor to good good	poor	poor to fair
Ease of Check Reading in Array of Controls	good	good	poor[a]	good	good[b]	poor	good
Ease of Operation in Array of Controls	poor	good	good	good	poor	good	good
Effectiveness as Part of a Combined Control	fair	fair	good	good	good[c]	good	good

[a] Exception is when control is back-lighted and light comes on when control is activated
[b] Application only when control makes less than one rotation; round knobs must also have a pointer
[c] Effective primarily when mounted concentrically on one axis with other controls

Key Terms

Continuous controls; control coding; control placement; control selection; design trade-offs; discrete controls; lever controls; pushbuttons; rotary selector switches; thumbwheel switches; toggle switches

General Description

Table 1 summarizes design factors to be considered when selecting a control for a particular application. Only the more common control types are listed and the relative comparison of each type for a particular design factor is stated in general, qualitative terms. No weighting is given to these factors since the designer must determine the relative importance of each for a specific application.

Applications

The selection of appropriate control types based on their relative effectiveness in a given design application.

Constraints

- The unique application for which a control is to be used may substantially affect the appropriateness of a control type and may require the designer to re-evaluate the relative effectiveness of various controls, rather than rely on the general guidance of Table 1.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

1. McCormick, E. J., & Sanders, M. S. (1982). *Human factors in engineering and design*. New York: McGraw-Hill.

*2. Van Cott, H. P., & Kinkade, R. G. (Eds.) (1972). *Human engineering guide to equipment design*. Washington, DC: American Institute for Research.

Cross References

12.101 Recommended uses of controls;

12.301 Principles of grouping and arranging controls;

12.412 Control type, location, and turbulence: effect on data entry performance

12.201 Control/Display Ratios

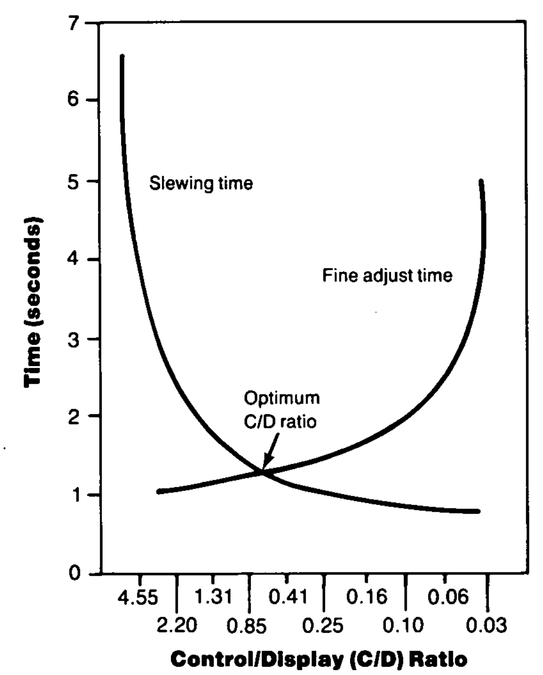


Figure 1. Time for primary movement ("slewing time") and for subsequent fine adjustment of a control as a function of the control/display ratio (i.e., control movement/display movement). (From Ref. 2)

Key Terms

Continuous rotary controls; control movements; control sensitivity; joysticks; linear control; linear displays; time delay

General Description

The control/display (C/D) ratio deals with the relative movement between a control and its associated display element (e.g., pointer, scale, cursor, etc.) and applies only to continuous controls. Where a large amount of control movement results in a small amount of display element movement, a high C/D ratio exists, and the control is considered to have low sensitivity. Where a small amount of control movement results in a large amount of display element movement, a low C/D ratio exists and the control is considered to have high sensitivity. C/D ratios for various control/display types are defined as follows:

Linear control (e.g., lever)/*linear display*: C/D = ratio of the control's linear displacement to the resulting display element displacement.

Linear control (e.g., joystick)/*linear display*: C/D = (a/360 x $2\pi L$)/display movement, where a = angular movement of control in degrees and L = length of joystick.

Continuous-rotary control/linear display: C/D = reciprocal of the display movement in centimeters for one complete revolution of the knob.

Generally two types of movement must be accomplished in positioning a continuous control: a slewing movement to rapidly move the control near its desired location, and a fine adjustment to place the control precisely in the final desired location. The optimum ratio is that which minimizes the total time required to make these two movements. Figure 1 illustrates how these can interact to influence the optimum C/D ratio.

Several factors may affect the optimum C/D ratio:

Display size: with control placement accuracy held constant, increasing the display size will decrease adjustment time.

Tolerance: when accuracy tolerances are eased, both fine-adjustment time and slewing time and may be reduced.

Time delay: the type and extent of any system response lag may affect the C/D ratios; in general, the longer the exponential lag between control movement and display response, the smaller the optimum C/D ratio.

For joystick controls, the optimum C/D ratio usually ranges from 2.5:1-4:1, while for continuous rotary controls, the range is usually 0.08-0.3. However, such values can only be considered "ballpark" figures. Because of the many variables involved, an optimum C/D ratio can only be empirically determined by stimulating the control task using various C/D ratios and a representative sample of the user population.

Key References

1. McCormick, E. J., & Sanders, M. S. (1982). *Human factors in engineering and design*. New York: McGraw-Hill.

*2. Van Cott, H. P., & Kinkade, R. G. (1972). *Human engineering guide to equipment design*. Washington, DC: American Institute for Research.

3. Woodson, W. E. (1981). *Human factors design handbook*. New York: McGraw-Hill.

Cross References

12.101 Recommended uses of controls;

12.102 Comparison of common controls;

12.301 Principles of grouping and arranging controls;

12.302 Guidelines for control/display position and movement relationships

12.301 Principles of Grouping and Arranging Controls

Key Terms

Criticality principle; functional control grouping

General Description

From a human engineering standpoint, control panel layout should take into account the following design principles:

Criticality: Locate the most critical or important (damage, injury) controls where visibility and accessibility are high and activation is easy.

Frequency: Locate the most often used controls for easy visibility and activation.

Functional Grouping: Group controls that are functionally related in terms of system operation.

Sequence-of-Use: Arrange controls in order of use for quick error-free activation, usually top-to-bottom or left-to-right.

Consistency of Operation: Components or component groups on more than one panel should have the same relative location, as far as feasible, on every panel.

System Flow: Arrange controls according to physical or functional interrelationships.

Applications

Control panel designs.

Constraints

- No single principle is consistently paramount across all applications; the relative importance of the principle must be determined on a per-case basis.
- Sequence-of-use is most applicable where operational requirements involve the use of controls in very repetitive sequences.
- System flow is most applicable to process control applications.

Key References

1. McCormick, E. J., & Sanders, M. S. (1982). *Human factors in engineering and design*. New York: McGraw-Hill.

2. Van Cott, H. P., & Kinkade, R. G. (Eds.) (1972). *Human engineering guide to equipment design*. Washington, DC: American Institute for Research.

Cross References

12.101 Recommended uses of controls;

12.102 Comparison of common controls;

12.412 Control type, location, and turbulence: effect on data entry performance

Notes

12.302 Guidelines for Control/Display Position and Movement Relationships

Key Terms

Clockwise-for-increase principles; control placement; control/display placement; data displays; linear displays; population stereotypes; scale-side principles; Warrick's principle

General Description

Proper control/display (C/D) relationships ensure unambiguous associations of controls with their displays and predictable display movements (and system responses). Population stereotypes (expectancies) of C/D relationships exist, but not all are strong. Guidelines are presented here for C/D position and movement relationships when controls and associated displays are mounted in the same plane.

Position Relationships

In general, the relationship between a control and its associated display is clearer when the control is directly below or to the right of the display. Figure 1 illustrates ways of arranging C/D components to improve their association when controls cannot be located directly below or to the right of associated displays.

Movement Relationships

Expected C/D movement relationships are influenced by C/D types. When C/D movements are congruous (i.e., both linear or both rotary), the stereotype is that they move in corresponding directions (e.g., both up, both clockwise, etc). When C/D movements are incongruous (e.g., rotary control and linear display), their movement relationship is harder to predict.

Several principles apply to the use of rotary controls with moving-pointer/fixed-scale linear displays. The clockwise-for-increase principle states that subjects expect clockwise control rotation to cause an increase in displayed value, except for flow values, where counterclockwise rotation is expected to increase flow. Warrick's principle states that when the axis of rotation of a control is perpendicular to the line of movement of a linear display, subjects expect the indicator to move in the same direction as the part of the control nearest the display. The scale-side principle states that subjects expect a pointer to move in the same direction as the side of the control knob that is on the same side as the scale markings or, in the absence of markings, the side where the indicator points. The three principles interact. When all are in agreement, strong stereotypes result. If they act in opposition, stereotypes may be weak or non-existent (Fig. 2).

The following principles apply to rotary controls used to make settings on fixed pointer/moving scale circular displays (Ref. 1). Scale numbers should increase from left to right. A scale should rotate in the same direction as its control. Controls should rotate clockwise to increase settings (except flow values).

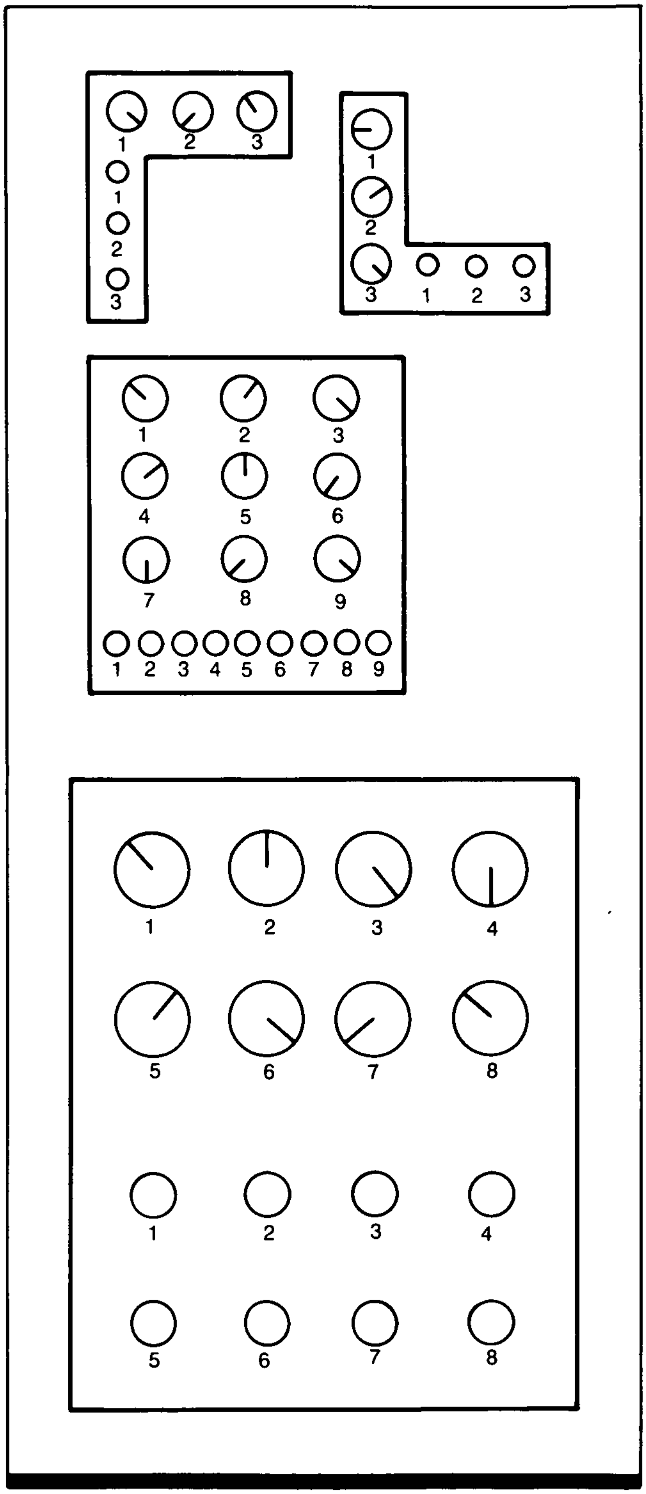


Figure 1. Suggestions for arranging controls to improve their association with displays when controls cannot be located directly below or to the right of associated displays. (From Ref. 4)

Empirical Validation

Some empirical data exist to support the principles, but the data are not complete and are not always consistent.

Constraints

- Population stereotypes can vary among cultures.
- Movement stereotypes have been investigated for only a few C/D combinations. Generalizability of findings beyond the test case is not known and should be verified empirically.
- The principles presented here apply only to controls and displays mounted in the same plane. Little research has addressed C/D relationships when controls and displays are mounted in different planes. Findings are not consistent.

Key References

1. Bradley, J. V. (1954, September). *Desirable control-display relationships for moving-scale instruments* (WADC TR 54-423). Wright-Patterson Air Force Base, OH: Wright Air Development Center. (DTIC No. AD061819)

2. McCormick, E. J., & Sanders, M. S. (1982). *Human factors in engineering and design*. New York: McGraw-Hill.

*3. Petropoulos, H., & Brebner, J. (1981). Stereotypes for direction-of-movement of rotary controls associated with linear displays: The effects of scale presence and position of pointer direction, and distances between the control and the display. *Ergonomics, 24*, 143-151.

*4. Van Cott, H. P., & Kinkade, R.G. (Eds.), (1972). *Human engineering guide to equipment design*. Washington, DC: American Institute for Research.

Cross References

12.101 Recommended uses of controls;

12.102 Comparison of common controls;

12.201 Control/display ratios;

12.301 Principles of grouping and arranging controls

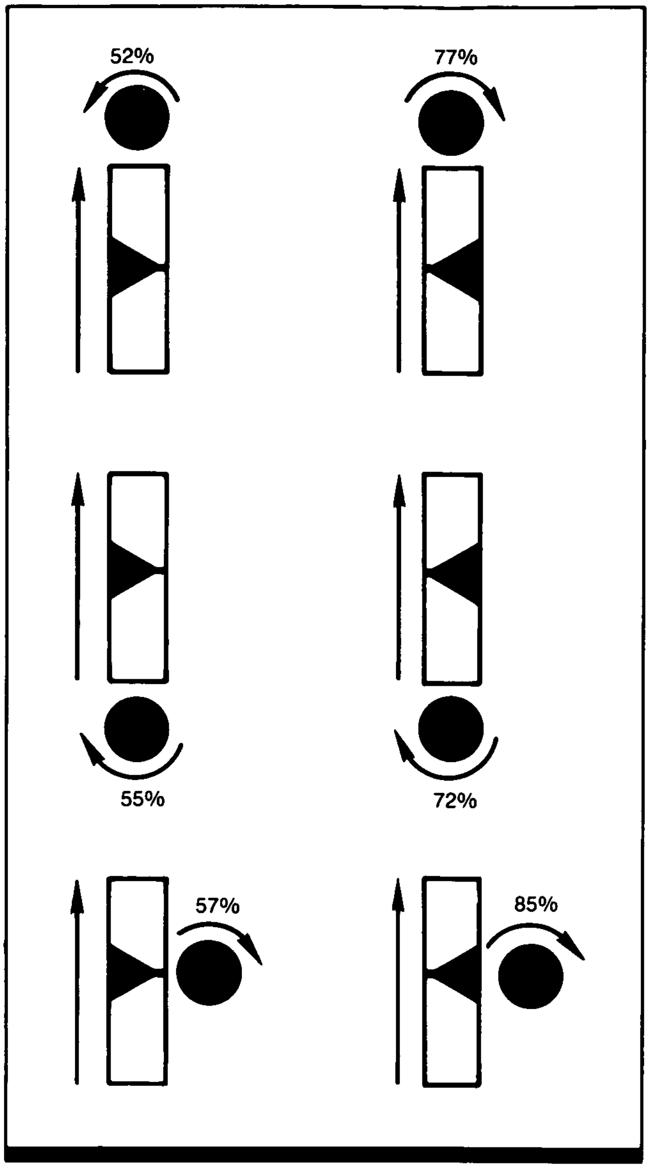


Figure 2. Six possible control/display configurations with related movements shown by the arrows. Values indicate the percentage of subjects expecting the control/display movements to be related as shown. (From Ref. 3)

12.303 Recommended Minimum Distances Between Controls

Key Terms

Continuous rotary controls; control placement; control separation; edge-to-edge measurement; J-handles; key-operated switches; legend switches; pushbuttons; rocker switches; rotary selector switches; slide switches; thumbwheel switches; toggle switches

General Description

Table 1 lists the minimum recommended distances between various control types both singularly and, when appropriate, in an array. Figure 1 illustrates how the measurements are made for the different controls.

Constraints

- These minimum separations are for bare-handed operations; when gloves are worn, separations must be increased accordingly.

Key References

*1. Nuclear Regulatory Commission. (1981). *Guidelines for control room design reviews* (NUREG-0700). Washington, DC: Government Printing Office.

Cross References

12.101 Recommended uses of controls;

12.102 Comparison of common controls;

12.201 Control/display ratios;

12.301 Principles of grouping and arranging controls;

12.302 Guidelines for control/display position and movement relationships;

12.304 Military aviator reach envelopes for placement of controls

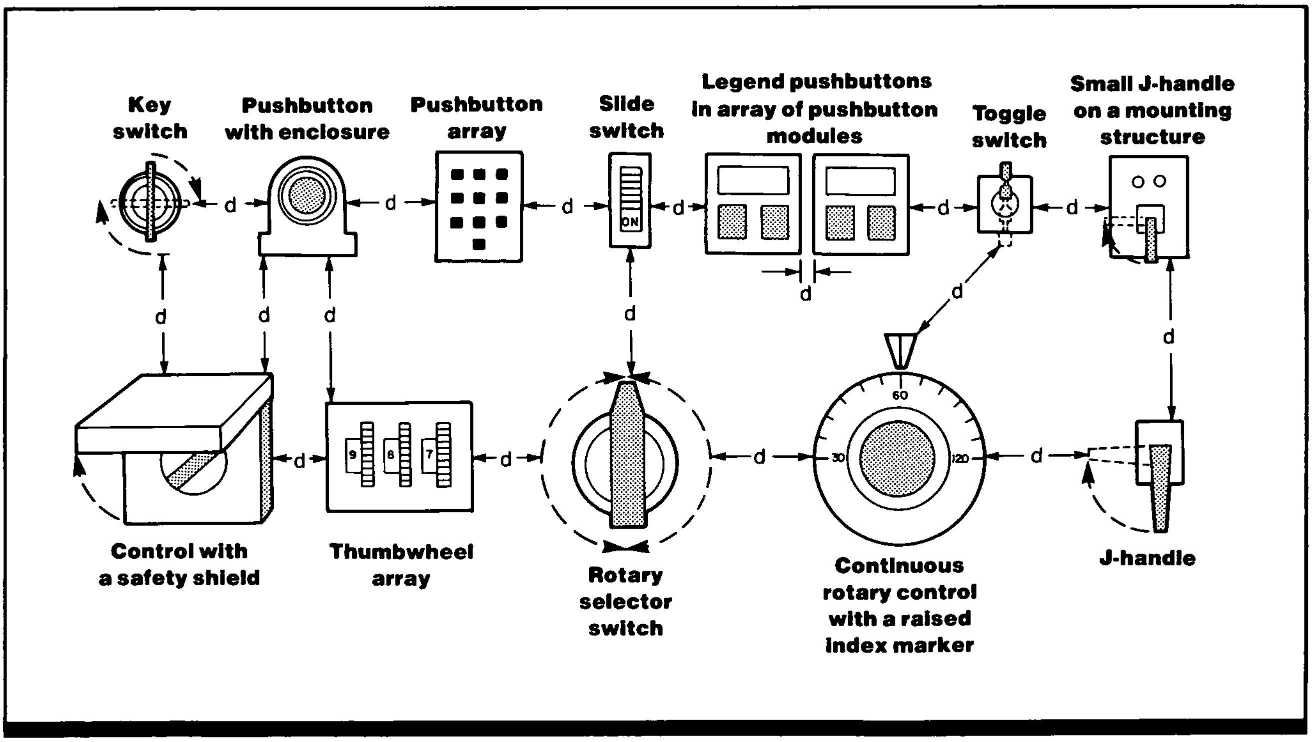


Figure 1. Measuring separation between controls. Distances (d) are measured from edge-to-edge of maximum rotation (or movement) envelope of the control. (From Ref. 1)

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Recommended minimum control separation in inches (centimeters). (From Ref. 1)

Control	Key-Operated Controls	Push-buttons Not in an Array	Push-button Arrays	Legend Switches, Legend Switch Array	Slide Switches, Rocker Switches	Toggle Switches	Thumb-wheels, Thumb-wheel Arrays	Rotary Selector Switches	Continuous Rotary Controls	J-Handles (Large)	J-Handles (Small)
Key-Operated Controls	1.0 (2.54)	0.5 (1.27)	1.5 (3.81)	1.0 (2.54)	0.75 (1.91)	0.75 (1.91)	0.5 (1.27)	0.75 (1.91)	0.75 (1.91)	5.0 (12.70)	2.0 (5.08)
Pushbuttons Not in an Array	0.5 (1.27)	0.5 (1.27)	2.0 (5.08)	2.0 (5.08)	0.5 (1.27)	0.5 (1.27)	0.5 (1.27)	0.5 (1.27)	0.5 (1.27)	6.0 (15.24)	3.0 (7.62)
Pushbutton Arrays[1]	1.5 (3.81)	2.0 (5.08)	2.0 (5.08)	2.0 (5.08)	1.5 (3.81)	1.5 (3.81)	1.5 (3.81)	2.0 (5.08)	2.0 (5.08)	6.0 (15.24)	3.0 (7.62)
Legend Switches, Legend Switch Arrays[2]	1.0 (2.54)	2.0 (5.08)	2.0 (5.08)	2.0 (5.08)	1.5 (3.81)	1.5 (3.81)	1.5 (3.81)	2.0 (5.08)	2.0 (5.08)	6.0 (15.24)	3.0 (7.62)
Slide Switches, Rocker Switches	0.75 (1.91)	0.5 (1.27)	1.5 (3.81)	1.5 (3.81)	0.5 (1.27)	0.75 (1.91)	0.5 (1.27)	0.5 (1.27)	0.5 (1.27)	5.0 (12.70)	2.0 (5.08)
Toggle Switches[3]	0.75 (1.91)	0.5 (1.27)	1.5 (3.81)	1.5 (3.81)	0.75 (1.91)	0.75 (1.91)	0.5 (1.27)	0.75 (1.91)	0.75 (1.91)	6.0 (15.24)	3.0 (7.62)
Thumbwheels, Thumbwheel Arrays	0.5 (1.27)	0.5 (1.27)	1.5 (3.81)	1.5 (3.81)	0.5 (1.27)	0.5 (1.27)	0.5 (1.27)	0.75 (1.91)	0.75 (1.91)	5.0 (12.70)	2.0 (5.08)
Rotary Selector Switches	0.75 (1.91)	0.5 (1.27)	2.0 (5.08)	2.0 (5.08)	0.5 (1.27)	0.75 (1.91)	0.75 (1.91)	1.0 (2.54)	1.0 (2.54)	5.0 (12.70)	2.0 (5.08)
Continuous Rotary Controls	0.75 (1.91)	0.5 (1.27)	2.0 (5.08)	2.0 (5.08)	0.5 (1.27)	0.75 (1.91)	0.75 (1.91)	1.0 (2.54)	1.0 (2.54)	5.0 (12.70)	2.0 (5.08)
J-Handles (Large)	0.5 (12.70)	6.0 (15.24)	6.0 (15.24)	6.0 (15.24)	5.0 (12.70)	6.0 (15.24)	5.0 (12.70)	5.0 (12.70)	5.0 (12.70)	3.0 (7.62)	5.0 (12.70)
J-Handles (Small)	2.0 (5.08)	3.0 (7.62)	3.0 (7.62)	3.0 (7.62)	2.0 (5.08)	3.0 (7.62)	2.0 (5.08)	2.0 (5.08)	2.0 (5.08)	5.0 (12.70)	1.0 (2.54)

[1] Pushbuttons within an array, 0.75 in. (1.91 cm) center-to-center.

[2] Legend switches within an array, no minimum distance, but should be separated by a barrier. Barrier should be at least 0.125 in. (0.318 cm) wide, 0.183 in. (0.465 cm) high, with rounded edges. Legend switches manufactured as elements of a modular array may be mounted as closely as engineering considerations permit.

[3] Toggle switches arrayed in horizontal line, 0.75 in. (1.91 cm) center-to-center.

12.304 Military Aviator Reach Envelopes for Placement of Controls

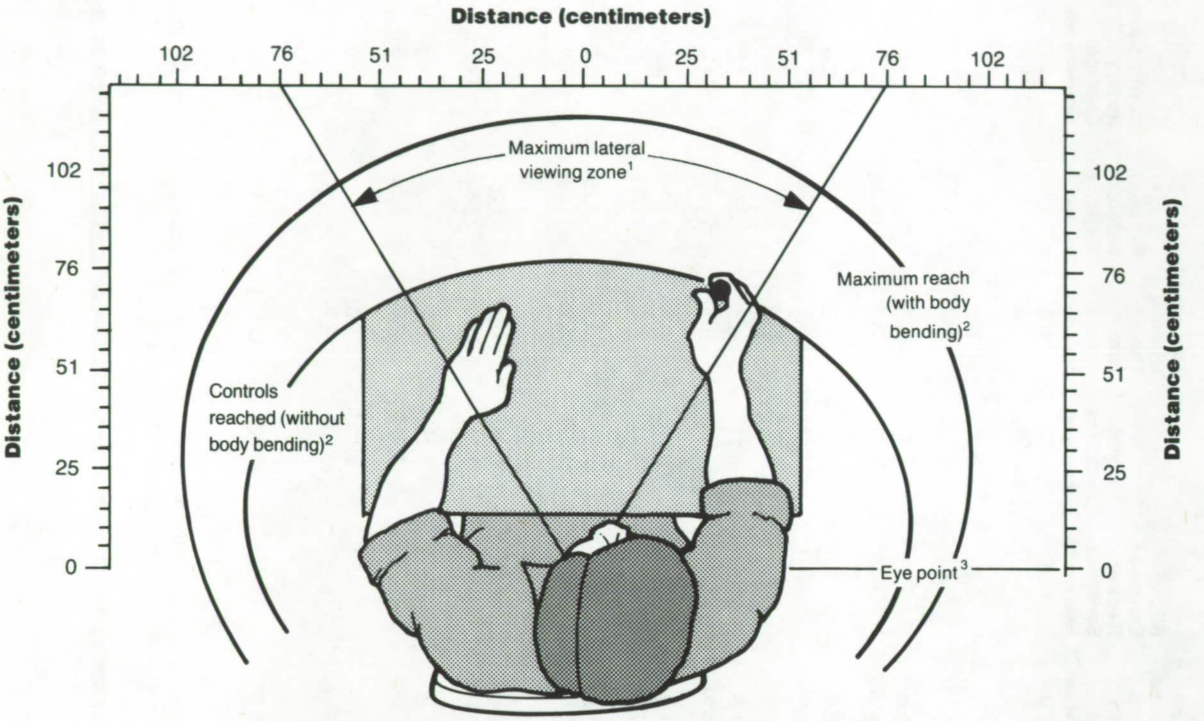


Figure 1. Forward and lateral reach envelopes for seated operations. (From Ref. 1)

[1] 71 cm forward of the eye point is the maximum distance for displays when viewing is limited by reach (control-display relationship). Viewing distance may be extended provided display is properly designed. Greater lateral spread of displays would require a wraparound panel.

[2] Based on 5th percentile male data; less for 5th percentile females.

[3] Console edge approximately 10-15 cm forward of eye point for 5th-95th percentile.

Key Terms

Anthropometry; control placement; eye position; lateral reach; operator reach envelopes

General Description

In the design of control panels, it is critical to consider control placement. To ensure that a large segment of the user population can readily reach a given control, anthropometric measurements are used to establish a range that will be suitable for 90% of the intended population. That is, lateral reach values at the 5th and 95th percentiles are used to specify a lateral reach envelope. Figure 1 illustrates the lateral reach envelopes for the seated 5th percentile operator. Table 1 provides anthropometric data for standing operations, and Table 2 provides the same information for seated operations.

Empirical Validation

The data are based on anthropometric measurements of military populations.

Constraints

- Because of human variability, the data are useful only for groups similar in age, ethnic background, etc., to the original population measured.
- Standing data should be adjusted for shoe height.

Key References

*1. Nuclear Regulatory Commission (1981). *Guidelines for control room design reviews* (NUREG-0700). Washington, DC: U. S. Government Printing Office.

*2. U.S. Army Missile Command (1981). *Human engineering design criteria for military systems, equipment and facilities* (MIL-STD-1472C). Philadelphia: Naval Publications and Forms Center.

3. Van Cott, H. P., & Kinkade, R. G. (Eds.) (1972). *Human engineering guide to equipment design*. Washington, DC: American Institute for Research.

Cross References

12.301 Principles of grouping and arranging controls;

12.302 Guidelines for control/display position and movement relationships;

12.303 Recommended minimum distances between controls

Table 1. Anthropometric data for standing operations in inches (centimeters). (Data from Ref. 2)

	5th Percentile		95th Percentile	
	Males (Aviators)	Females	Males (Aviators)	Females
Shoulder Height (above standing surface)	52.5 (133.3)	48.4 (123.0)	60.9 (154.8)	56.6 (143.7)
Functional Reach	28.8 (73.1)	25.2 (64.0)	34.3 (87.0)	31.7 (80.4)

Table 2. Anthropmetric data for seated operations in inches (centimeters). (Data from Ref. 2)

	5th Percentile		95th Percentile	
	Males (Aviators)	Females	Males (Aviators)	Females
Shoulder Height (above seating surface)	21.5 (54.6)	19.6 (49.9)	25.9 (65.9)	23.7 (60.3)
Functional Reach	28.8 (73.1)	25.2 (64.0)	34.3 (87.0)	31.7 (30.4)

12.401 Pushbuttons: Effects of Spacing, Diameter, and Orientation on Error Rate

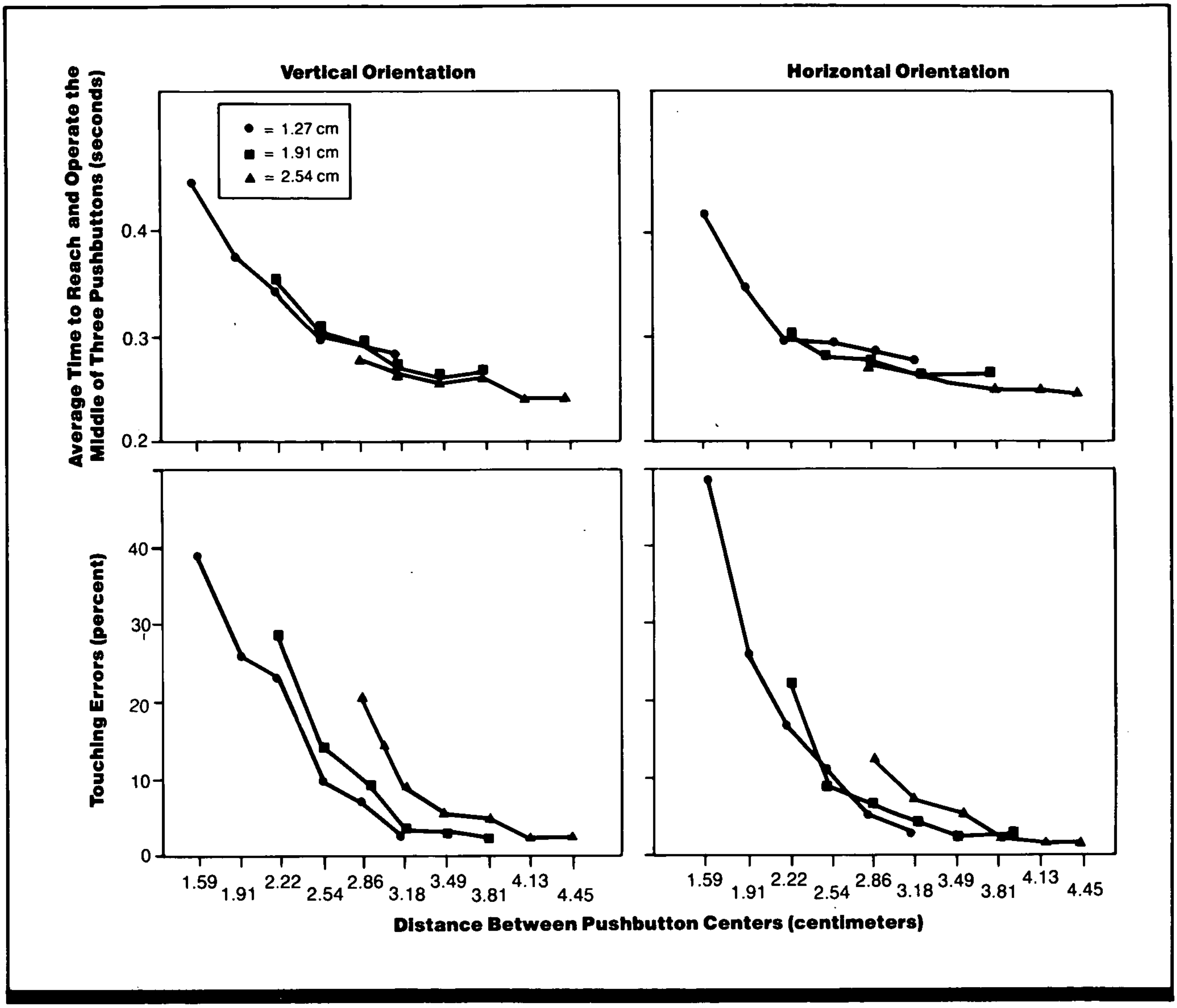


Figure 1. Operating speed and touching errors for pushbutton controls as a function of center-to-center spacing for pushbuttons of three different diameters. (From Ref. 2)

Key Terms

Control separation; operating errors; pushbuttons

General Description

When the distance between the center of pushbuttons is held constant (i.e., panel space is scarce), reducing pushbutton control diameter has a negligible effect on speed of operation of pushbuttons, but touching errors decrease. When the distance between the edges of pushbuttons is held constant (i.e., panel space is abundant), operating speed is faster, and fewer touching errors occur with larger diameter controls. Performance is better (both in terms of speed and errors) when pushbuttons are arranged in a horizontal rather than a vertical array.

Methods

Test Conditions

- Operated control mounted in center of 40.6- × 40.6-cm panel, flanked by other identical controls
- 1.27-cm diameter amber light mounted 5.08 cm above top of panel edge; illuminated at start of trial, extinguished when center pushbutton actuated
- Telegraph key mounted 6.35 cm above lower edge and 14 cm in front of panel face, released by subject when signal light was illuminated to start timing

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: pushbutton diameters (1.27, 1.91, and

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

2.54 cm); between-control spacing (0.32-1.91 cm in 0.32-cm increments); control orientation (vertical or horizontal)
• Dependent variables: operating time, defined as time from release of telegraph key until the center pushbutton was actuated; touching error is the inadvertent contact of subject's hand with an adjacent pushbutton; operating error is the inadvertent operation of an adjacent pushbutton
• Subject's task: release telegraph key, actuate center pushbutton
• 36 subjects, right-handed male college students

Experimental Results

• When the distance between control centers is held constant, diameter has a negligible effect upon operation time, but touching errors decrease with decreases in diameter.
• When the distance between control edges is held constant, both operation time and touching errors decrease as diameter is increased.
• All performance measures show improvement when controls are arranged in a horizontal rather than a vertical array.
• Significant main effects ($0.01 < p < 0.025$) are found for spacing, diameter, and orientation for both operating time and touching errors.
• Significant interactions ($0.01 < p < 0.05$) are found for all independent variables for operation time, but only the spacing-by-diameter interaction was significant ($p < 0.05$) for touching errors.
• No formal analysis of operating errors is reported, but the authors feel the results parallel those found with touching errors.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Similar results were obtained by Bradley (Ref. 1) regarding spacing, diameter, and orientation of continuous rotary controls.

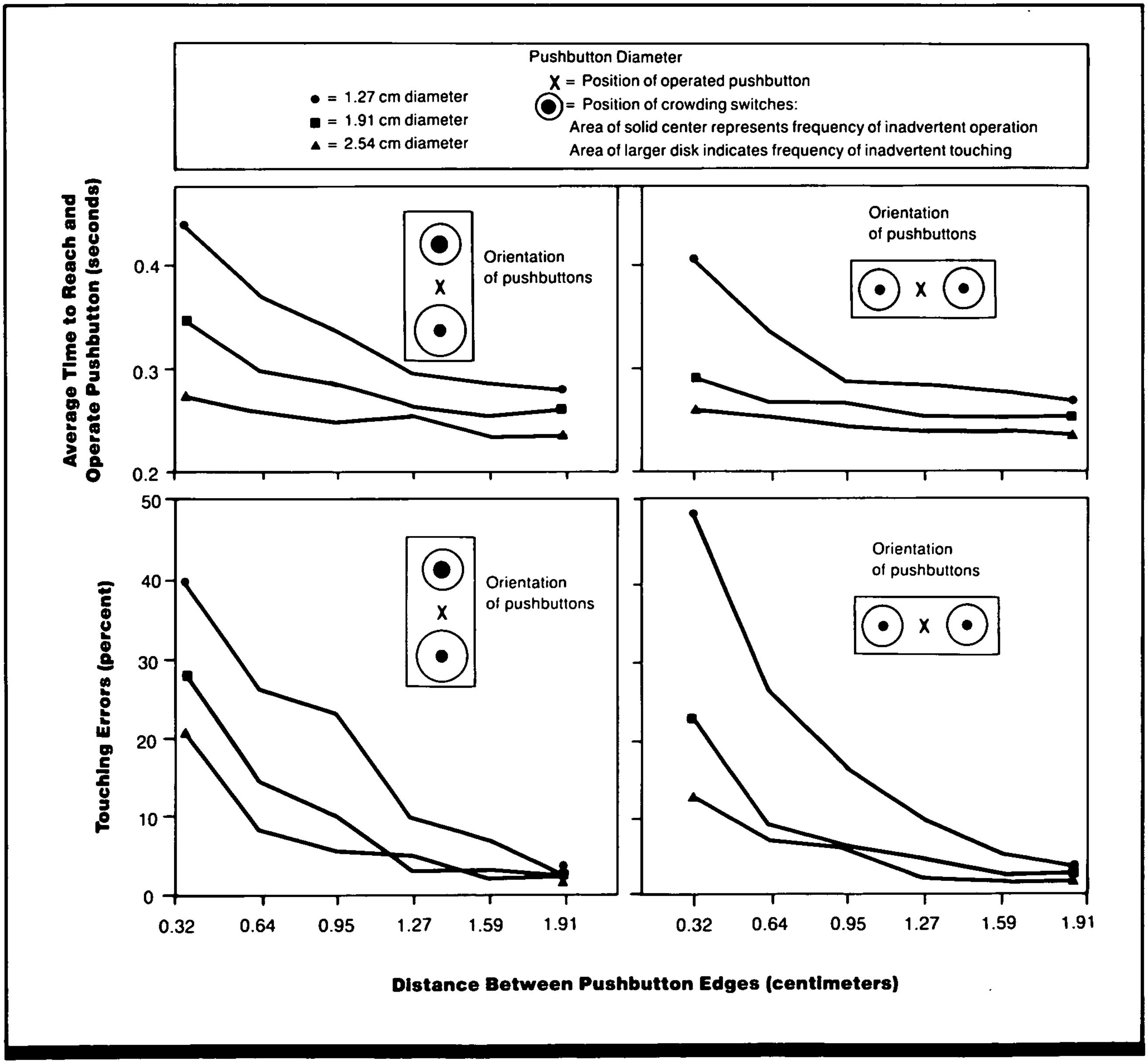


Figure 2. Operating speed and touching errors for pushbutton controls as a function of edge-to-edge spacing for pushbuttons of three different diameters. (From Ref. 2)

Constraints

- The statistical analysis of the data violated some assumptions (e.g., normality and homogeneity) of the model involved, which may have slightly inflated the observed significance levels.

Key References

1. Bradley, J. V. (1969). Optimum knob crowding. *Human Factors, 11*, 227-238.

*2. Bradley, J. V., & Wallis, R. A. (1958, April). *Spacing of on-off controls. 1: Pushbuttons* (WADC-TR 58-2). Wright-Patterson Air Force Base, OH: Wright Air Development Center. (DTIC No. AD142272)

Cross References

12.303 Recommended minimum distances between controls;

12.404 Toggle switches: effects of spacing, orientation, and direction of throw on error rate;

12.416 Rotary controls: spacing, diameter, and orientation

Notes

12.402 Transilluminated Pushbutton Indicators: Effects of Display Color and Ambient Illumination on Reaction Time

Key Terms

Cockpit lighting; color coding; color displays; dark adaptation; pushbutton indicators; reaction time

General Description

Reaction time to transilluminated pushbutton indicators (PBIs) decreases as ambient illumination levels increase from very low to normal. At a low level of red ambient illumination, reaction times are different for different colored PBIs (Fig. 1). Visual acuity also is poorer under low levels of red or white illumination than under normal white illumination levels. Acuity is almost identical under both low illumination levels tested, and is unaffected by either adapting to low red illumination followed by immediate exposure to low white illumination, or by the colors of the PBIs tested.

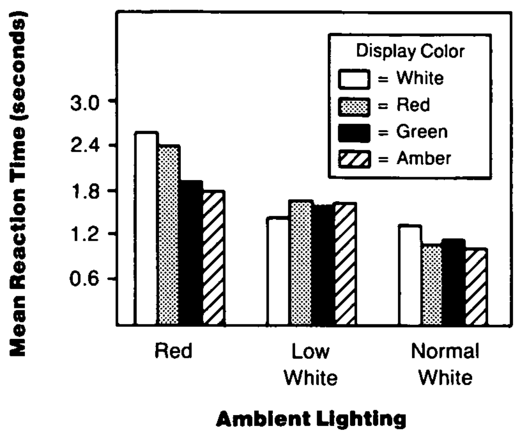


Figure 1. Effects of ambient lighting level and display color on response time. (From Ref. 1)

Methods

Test Conditions

- Light-tight room; method of illumination unspecified, but assumed to be uniform
- Display panel 48 x 28 cm containing three rows of ten horizontally split, back-illuminated PBIs; panel located in front of subjects, but exact location not specified
- Top half of each PBI always illuminated; illumination of bottom half controlled by experimenter; PBI colored and colorless interchangeable lenses; PBIs either red or another color; for red, ten transparent lenses with black engraving and 20 opaque black lenses with translucent engraving; for other color displays, ten sets of three PBIs each were: red, amber, green, white, red and amber, red and green, red and white, amber and green, amber and white, and green and white
- PBI average illumination for viewing under red and nominal (low) white ambient illumination: transparent PBIs 3.23 lux and translucent engraved PBIs 0.323 lux, a 10:1 ratio; PBI average illumination for viewing under normal white illumination: transparent PBIs 32.3 lux and translucent engraved PBIs 3.23 lux, a 10:1 ratio
- Subjects tested after 20-min adaptation period
- Order of presentation randomized; 30 trials per subject for each condition

Experimental Procedure

- Factorial design
- Independent variables: PBI color (red or another color); ambient illumination: red at 0.22 lux, low white at 0.22 lux, normal white at 215 lux; PBI position on panel
- Dependent variables: reaction time, defined as time (in sec) between illumination of bottom half of PBI and depressing PBI; visual acuity in undefined units, measured using Ortho-Rater visual test presented on a card rather than in Ortho-Rater apparatus
- Subject's task: identify the pushbutton indicator illuminated by the experimenter by depressing the indicator and extinguishing it
- 18 adult subjects with at least 20/30 uncorrected visual acuity

Experimental Results

- Spectral distribution and intensity of ambient lighting significantly ($p < 0.001$) affect reaction time (Fig. 1); reaction times are longest under red ambient lighting and shortest under normal white lighting. Low white lighting yields intermediate results.
- A significant difference is found in reaction times to PBI colors under red ambient conditions. Rates of response, from fastest to slowest, for the colors are amber, green, red, and white.
- Compared with acuity under the normal illumination condition, acuities are less but comparable across the other conditions tested (Fig. 2).
- Reaction times are different for various PBI panel conditions, but the data are not given here due to their limited generalizability.

Variability

No information on variability was given.

Constraints

- These findings may not be consistent for tasks, lighting conditions, or colors of ambient light which differ from those used in this study.
- Similar results may not be obtained in situations with more complex environments.

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Key References

*1. Carr, R. M. (1967). The effects of color coding indicator displays on dark adaptation. *Human Factors, 9*, 175-179.

Cross References

1.705 Factors affecting color discrimination and color matching;

1.710 Hue and chroma: shifts under daylight and incandescent light;

7.513 Search time: effect of number of colors and information density;

11.124 Dial scale reading times: effects of brightness contrast and color contrast;

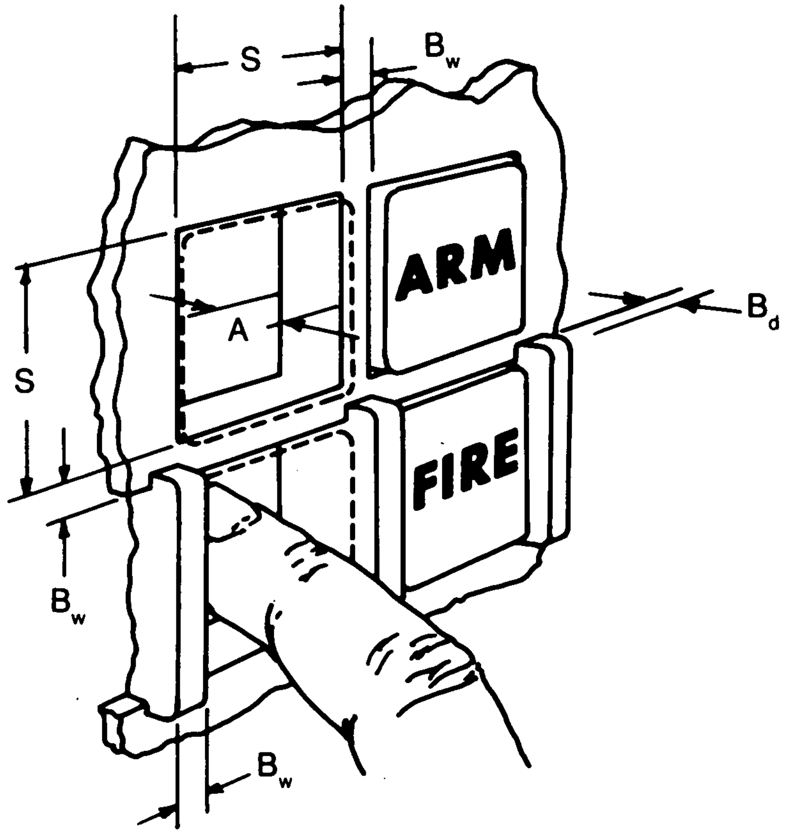
11.125 Effects on instrument reading performance: pointer, background, and panel lighting colors;

11.202 Redundant coding: use of color in conjunction with other codes;

11.203 Use of color coding: effect of display density;

11.205 Use of color coding: effect of symbol luminance, illumination level, and hue

12.403 Legend Switches



	S Size	A Displacement	Barriers* B_w	Barriers* B_d	Resistance
Minimum	19 mm (0.75 in.)	3 mm** (0.125 in.)	3 mm (0.125 in.)	5 mm (0.188 in.)	280 mN (10 oz)
Maximum	38 mm (1.5 in.)	6 mm (0.250 in.)	6 mm (0.250 in.)	6 mm (0.250 in.)	11 N (40 oz)

*Barriers shall have rounded edges.

**5 mm (3/16 in.) for positive position switches

Figure 1. Legend switch design recommendations. (From Ref. 1)

Key Terms

Discrete controls; legend switches

General Description

Figure 1 gives design parameters for legend switches. Table 1 delineates specific requirements pertinent to legend switch design.

Constraints

- Specific applications may require some modifications to these design recommendations.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. U.S. Army Missile Command. (1981). *Human engineering design criteria for military systems, equipment and facilities*. (MIL-STD-1472C). Philadelphia: Naval Publications and Forms Center.

Cross References

12.413 Rotary selector switches

Table 1. Legend switch design recommendations. (From Ref. 1)

Barriers
• Should be used on critical switches or others likely to be inadvertently activated • Should not obscure labels or displays or hinder physical access to controls • Should conform to dimensions in Fig. 1
Indication of Activation
• Provided by detent or click for electromechanical switches • Provided by integral light for touch-sensitive, nonmechanical switches
Legends
• Should be visible with or without internal illumination • Should be no longer than three lines of lettering on plate
To Minimize Maintenance
• Provide lamp test or dual filament bulbs (except where LEDs are used) • Bulbs should be replaceable from front cover • Covers should be keyed to prevent interchange

12.404 Toggle Switches: Effects of Spacing, Orientation, and Direction of Throw on Error Rate

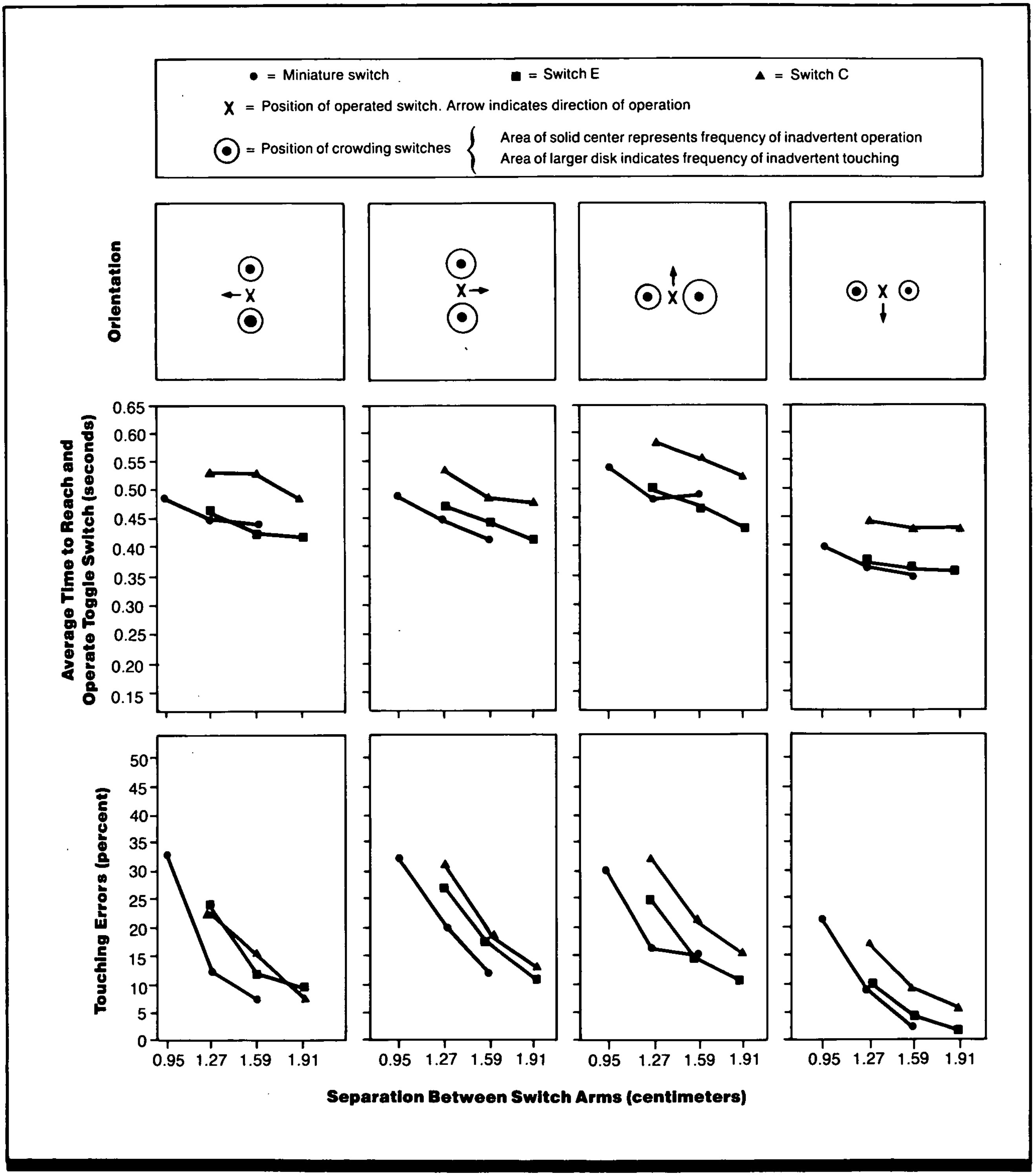


Figure 1. Operation time and touching errors for toggle switches as a function of control orientation and separation between switch arms. (From Ref. 2)

Key Terms

Control errors; control separation; toggle switches

General Description

Resistance of switches to activation is correlated positively with both speed of operation and inadvertent touching of adjacent controls, and negatively with inadvertent operation of adjacent controls. Miniature switches are superior to full-sized toggles in terms of operating time and touching errors, and can be expected to match them in terms of operation errors, given an equal resistance to actuation. Performance is better when toggles are arranged in a horizontal rather than a vertical array if the direction of throw is down. Where right or left throw is required, the vertical orientation is superior.

Methods

Test Conditions

- Subject's panel: operated control mounted in center of 40.6 × 40.6 cm panel (switch types M, C, or E with physical characteristics shown in Table 1) flanked by other identical controls
- 1.27-cm diameter amber light mounted 5.08 cm above top panel edge; illuminated at start of trial, extinguished when center toggle actuated
- Telegraph key mounted 6.35 cm above lower edge and 14 cm in front of panel face, released by subject when signal light was illuminated to start timing

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: switch type (see Table 1), orientation of array (vertical or horizontal), direction of throw, between-control spacing (for control types C and E: 1.27, 1.59, and 1.91 cm; for type M: 0.95, 1.27, and 1.59 cm)
- Dependent variables: operating time, the time from subject's release of telegraph key until the center toggle switch was actuated; touching error, the inadvertent contact of subject's hand with an adjacent toggle switch; operating error, the inadvertent operation of an adjacent toggle switch
- Subject's task: release telegraph key, actuate center toggle switch
- 36 subjects, right-handed male college students

Experimental Results

- For all switch types, both operating times and errors decrease as the separation between switches increases (Figs. 1, 2).
- The horizontal orientation with downward direction of throw results in minimum operating time and minimum errors.
- Operating time is shorter and touching errors fewer when the miniaturized switch (M) rather than switch E or switch C is used, but operating errors are more frequent with the miniaturized switch. The result is thought to be due to the lower activation resistance of the specific switch type tested.
- The main effect of direction of throw is not significant.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

A study by Bradley and Wallis (Ref. 1) examined pushbutton controls using the same experimental approach and a similar subject population. A comparison of the results indicates that when speed of operation is of primary importance, pushbutton controls (diameter 1.27 cm or more) with small resistance to operation should be used rather than toggle switches. However, when preventing inadvertent operation is of primary importance, and when controls must be placed <2.54 cm apart, toggle switches with large resistance to operation should be used.

Constraints

- The toggle switches varied across a number of physical parameters; therefore, observed performance differences cannot be attributed to any one switch characteristic.
- The statistical analysis of the data violated some assumptions (e.g., normality and homogeneity) of the model involved, which may have slightly inflated the observed significance levels.
- Analysis involving all three switches was confined to data for the 1.27- and 1.59-cm spacings, which were common to all.

Table 1. Toggle switch characteristics. (Adapted from Ref. 2)

	Switch		
Characteristics	M	E	C
Angle between perpendicular and toggle in "Off" position	20 deg	20 deg	0 deg
Angle traveled by toggle arm between "Off" and "On" positions	40 deg	40 deg	20 deg
Widest diameter of toggle arm	0.32 cm	0.60 cm	0.64 cm
Length of toggle arm (from tip to pivot point)	0.71 cm	1.82 cm	1.98 cm
Diameter of threaded cylinder in which toggle arm is pivoted	0.64 cm	1.19 cm	1.19 cm
Width of insulated housing of soldering lugs	0.87 cm	1.67 cm	1.59 cm

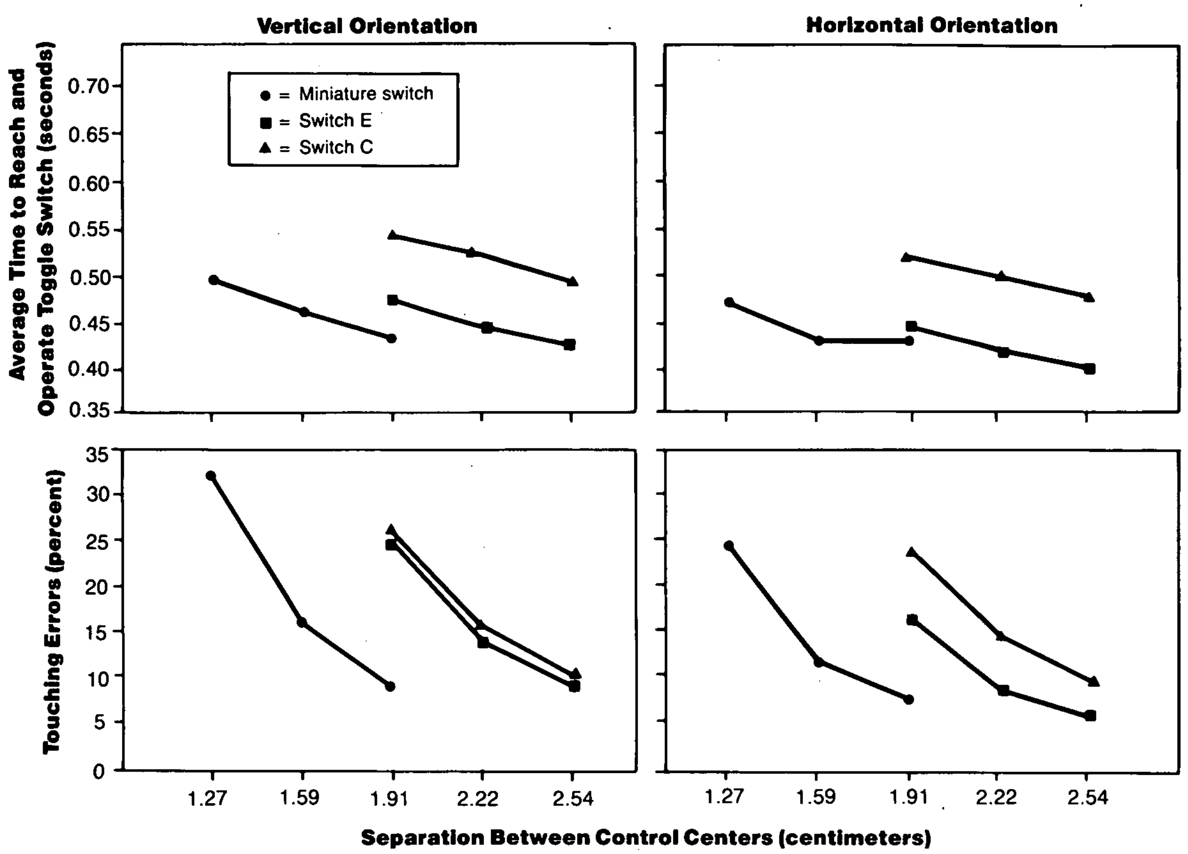


Figure 2. Operation time and touching errors for toggle switches as a function on control orientation and center-to-center spacing. (From Ref. 2)

Key References

1. Bradley, J. V., & Wallis, R. A. (1958, April). *Spacing of on-off controls. 1: Pushbuttons* (WADC-TR 58-2). Wright Patterson Air Force Base, OH: Wright Air Development Center.

*2. Bradley, J. V., & Wallis, R. A. (1960). Spacing of toggle switch on-off controls. *Engineering and Industrial Psychology, 2*(1), 8-19.

Cross References

7.113 Probability of correctly operating continuous controls while monitoring dynamic displays;

7.114 Probability of correctly operating continuous controls while monitoring and tracking dynamic displays;

12.303 Recommended minimum distances between controls;

12.401 Pushbuttons: effects of spacing, diameter, and orientation on error rate;

12.416 Rotary controls: spacing, diameter, and orientation

Notes

12.405 Toggle Switches: Factors Affecting Activation Time

Key Terms

Activation sequence; control complexity; control density; link multiplicity; toggle switches

General Description

Activation time is significantly related to number of controls, control density, activation sequence, control complexity, and link multiplicity. However, only three of these factors (number of controls, control density, and link multiplicity) are positively and linearly related to control activation time and felt to be of operational importance. The effect of activation sequence is too small to be considered in control panel evaluation. Control complexity was not significant in this study.

Methods

Test Conditions

- Three-position, bat-type toggle switches, with 2.22-cm switch arm, 14-N on and 6.2-N off force; mounted in 61 × 61-cm matrix board; cards in adjacent display panel indicated control operation for trial; light illuminated at start of trial, button to extinguish light
- Control number: 2-30; control density: 2.54-20.3 cm between centers; complexity: single or dual function controls; link multiplicity: one, three, or six display links per control; activation sequence: zero, six, or ten discontinuities of sequence (panel shown in Fig. 1c also rotated 90 deg); Fig. 1 illustrates control panel arrangement for various experiments

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: number of controls, control density, activation sequence, control complexity, link multiplicity
- Dependent variables: control activation time (defined as time from activation of first switch in a sequence until activation of last switch)
- Subject's task: when trial light is illuminated, push button to extinguish it and activate switches as indicated on display instruction card
- Right-handed subjects, male university students and staff, drawn in groups of three

Experimental Results

- Errors occur in <2% of the switch activations across all experiments.
- Activation time increases linearly with increases in the number of controls ($p < 0.001$).
- Activation time increases linearly (for most realistic situations) with increasing control density ($0.001 < p < 0.025$).
- Small and variable, although statistically significant ($p < 0.001$), differences in activation time are found when the number of discontinuities in an activation sequence is varied.
- There are slight but significant differences ($p < 0.01$) in activation time when two rows of single-throw switches are compared to double-throw switches for accomplishing the same operation.
- There is a significant increase ($p < 0.001$) in activation time as the number of links between a switch and its associated display is increased.
- Control complexity did not have a significant effect on activation time.

Variability

No information on variability was given.

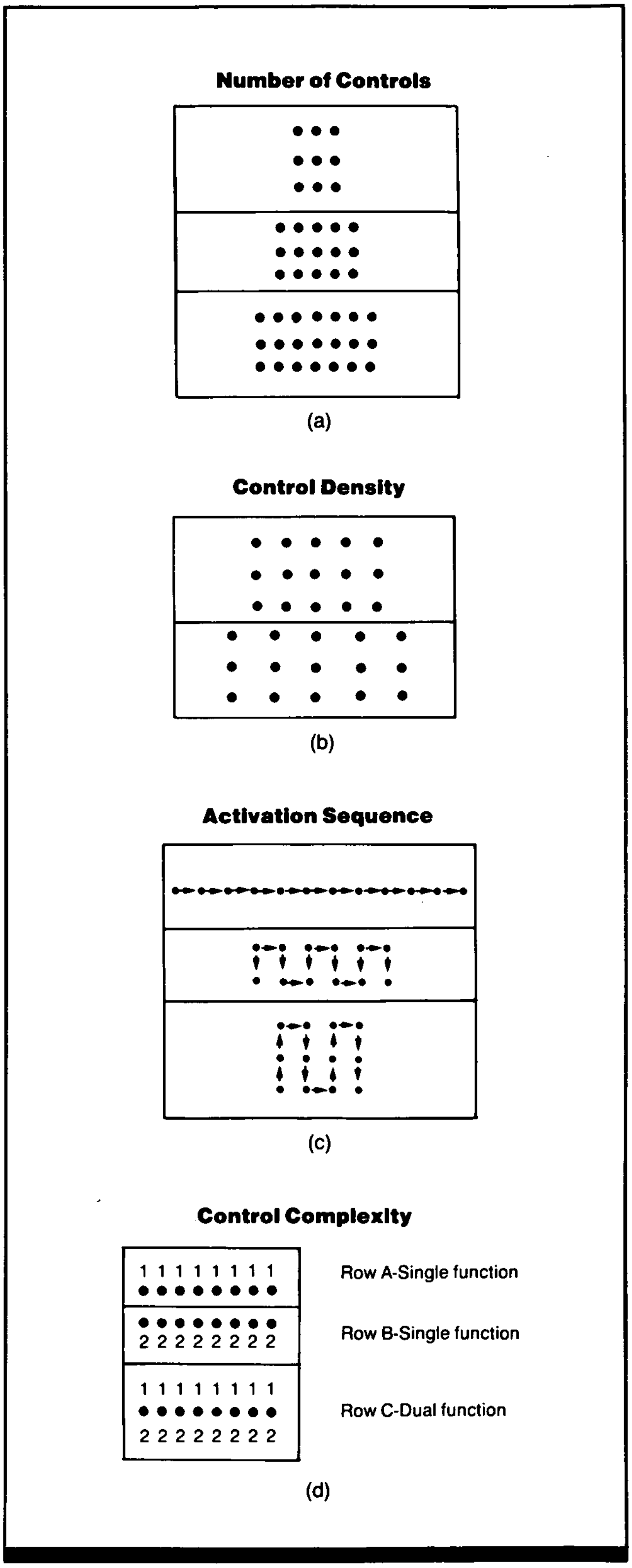


Figure 1. Examples of control panel arrangements for selected experiments. (From Ref. 1)

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Constraints

- Each experiment is based on a small sample size.

Key References

*1. Siegel, A. I., Shultz, D. G., & Lanterman, R. S. (1963). Factors affecting control activation time. *Human Factors, 5*, 71-80.

Cross References

9.106 Reaction time: effect of uncertainty;

9.202 One- versus two-handed reaching: effect of target distance and width;

9.203 Fitts' Law: movement and reation time as a function of target distance and size

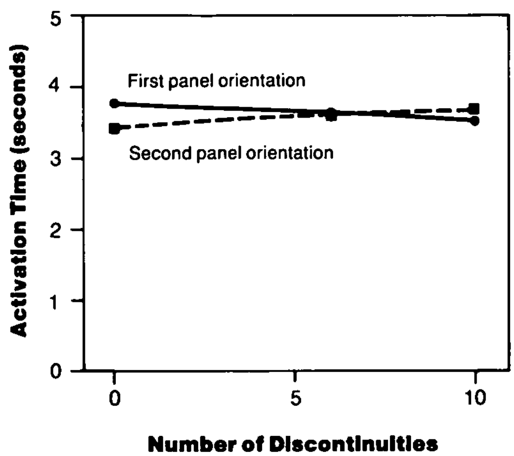

Figure 2. Mean control activation time as a function of the number of discontinuities and panel orientation. (From Ref. 1)

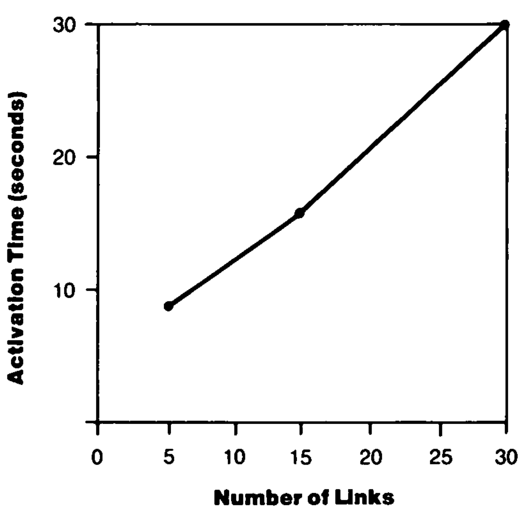

Figure 3. Mean activation time for five toggle switches as a function of the number of display links. (From Ref. 1)

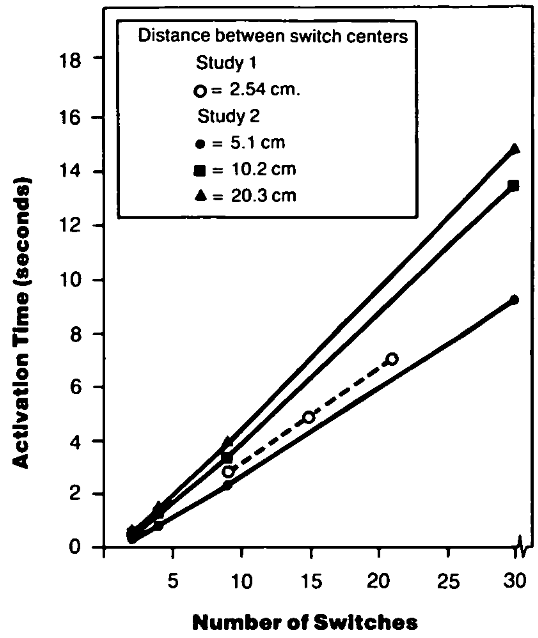

Figure 4. Average activation time as a function of number of controls and center-to-center control distance. The broken line represents mean trial times across subjects. (From Ref. 1)

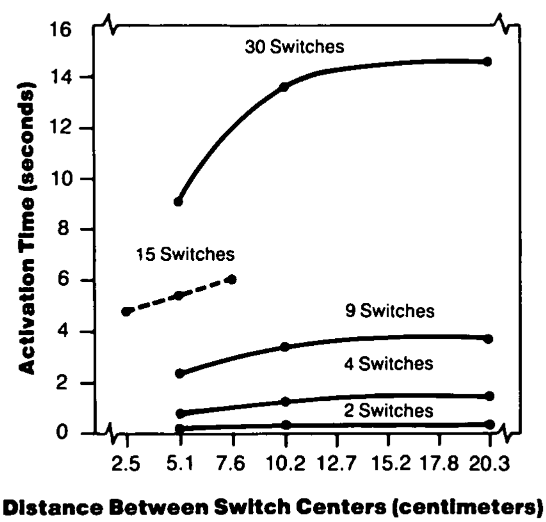

Figure 5. Average activation time as a function of center-to-center control distance and number of switches. The broken line represents mean trial times for each density. (From Ref. 1)

12.406 Numeric Keyset Arrangements: Effects on Speed and Accuracy of Data Entry

Key Terms

Calculator keysets; data entry; keysets; numeric keysets; telephone keysets

General Description

Keying performance is slightly faster and significantly more accurate with the telephone numeric keyset arrangement than with the calculator arrangement. Speed and accuracy of keying is also significantly better when the telephone arrangement is used exclusively, rather than alternately, with the calculator arrangement.

Methods

Test Conditions

- Two standard commercial add-listing machines; one with standard pushbutton telephone keyset arrangement:

```
1 2 3
4 5 6
7 8 9
  0
```

one with modified calculator arrangement:

```
7 8 9
4 5 6
1 2 3
  0
```

- Eight-digit codes visually presented, printed in columns, 1.5 spaces between digits, double vertical spacing between codes, drawn from random number tables
- One keyset arrangement or subjects alternated between arrangements

Experimental Procedure

- Random block design
- Independent variables: pushbutton keyset arrangement, one or two keysets, practice day
- Dependent variables: number of codes entered per minute; proportion of erroneously entered codes, uncorrected erroneously entered codes, erroneously entered digits, uncorrected erroneously entered digits, omitted digits, added digits
- Subject's task: read eight-digit code, input code on keyset
- Self-paced data entry; no extrinsic feedback provided
- 90 women, 30 per group, no experience with either keyset arrangement

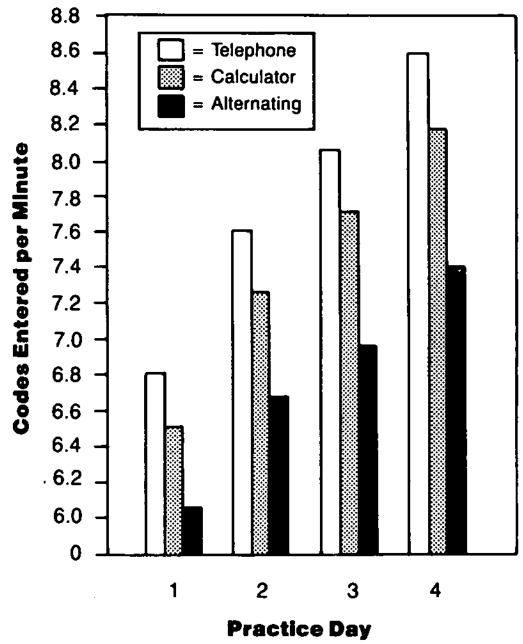

Figure 1. Numeric data-entry speed as a function of practice for subjects using only a standard telephone handset ten-key arrangement, only a standard calculator arrangement, or alternating between arrangements. (Data from Ref. 1)

Experimental Results

- Keying speed is significantly faster ($p < 0.05$) in the standard pushbutton telephone keyset (T) condition than in the alternating (A) condition.
- Keying speed is faster in the T condition than in the modified calculator (C) condition, but the difference is not significant.
- There is no significant difference in keying speed between the C and the A conditions.
- Keying performance in the T condition is significantly more accurate ($p < 0.001$) than in the C condition for every error measure shown in Fig. 2.
- Keying performance in the T condition is significantly more accurate ($0.001 < p < 0.05$) than keying performance with the telephone arrangement in the A condition for every error measure shown in Fig. 2.
- There is only one significant difference in keying accuracy between the C condition and the calculator arrangement in the A condition: the latter is significantly more accurate (level not stated) in terms of erroneously entered codes.
- Significantly more errors of omission ($p < 0.001$) and addition ($p < 0.01$) are committed in the C condition than in the T condition.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Lutz and Chapanis (Ref. 2) found that the most commonly expected arrangement of a $3 \times 3 + 1$ matrix was the pushbutton telephone arrangement.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

• Subjects unacquainted with either keyboard. Errors were still decreasing and speed increasing at the end of the study. For subjects well practiced with both arrangements, performance differences may be reduced.

• Considerable time has passed since this study was completed. Now both pushbutton telephones and pocket calculators have become commonplace. This familiarity with the arrangements might cause the performance differences shown here to be muted.

Key References

*1. Conrad, R., & Hull, A. J. (1968). The preferred layout for numerical data entry keysets. *Ergonomics, 11*, 165-173.

2. Lutz, M. C., & Chapanis, A. (1955). Expected locations of digits and letters on ten-button keysets. *Journal of Applied Psychology, 39*, 314-317.

Cross References

12.407 Conventional versus membrane keyboards;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.409 Keyboard slope: effect on keying performance;

12.410 Keyboards and keysets: effects of key size, force, displacement, and feedback on keying performance;

12.414 Selection of data entry devices: rotary selectors, thumbwheels, and pushbuttons;

12.415 Selection of data entry devices: ten-button keyset, matrix keyboard, vertical levers, and rotary selectors

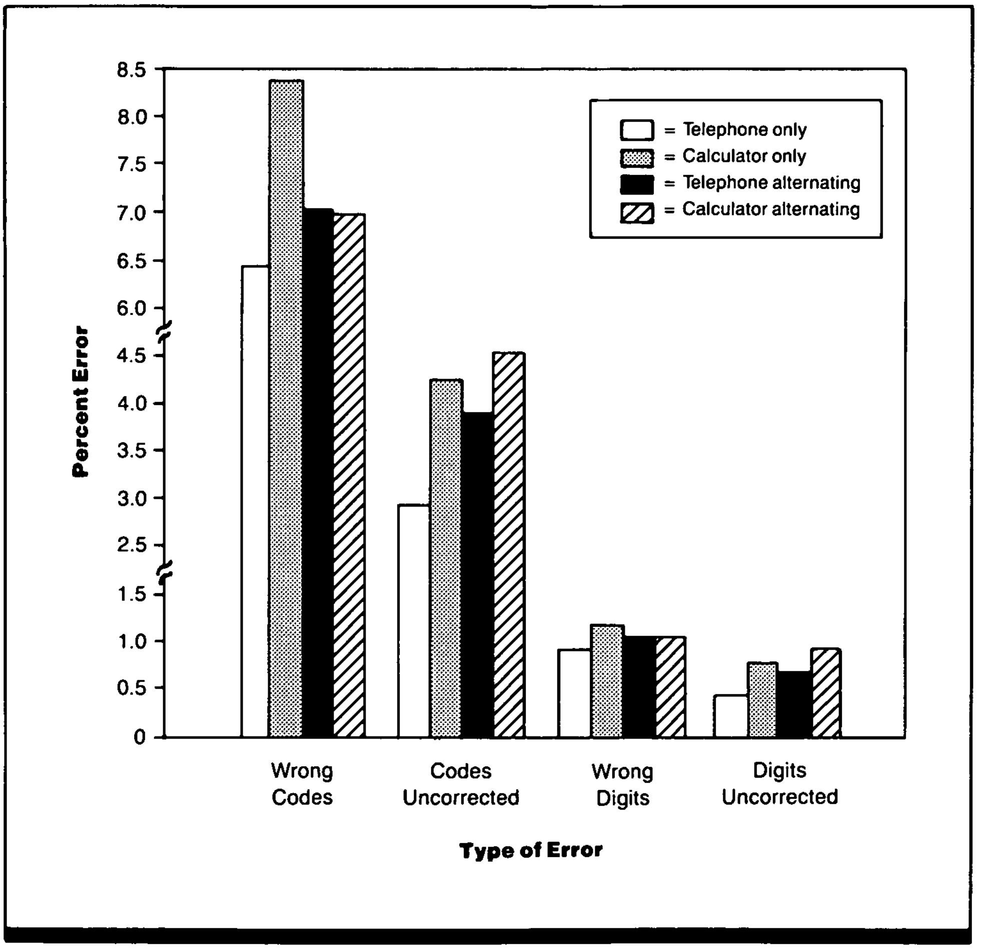

Figure 2. Accuracy of data entry for the same experiment. (Data from Ref. 1)

12.407 Conventional Versus Membrane Keyboards

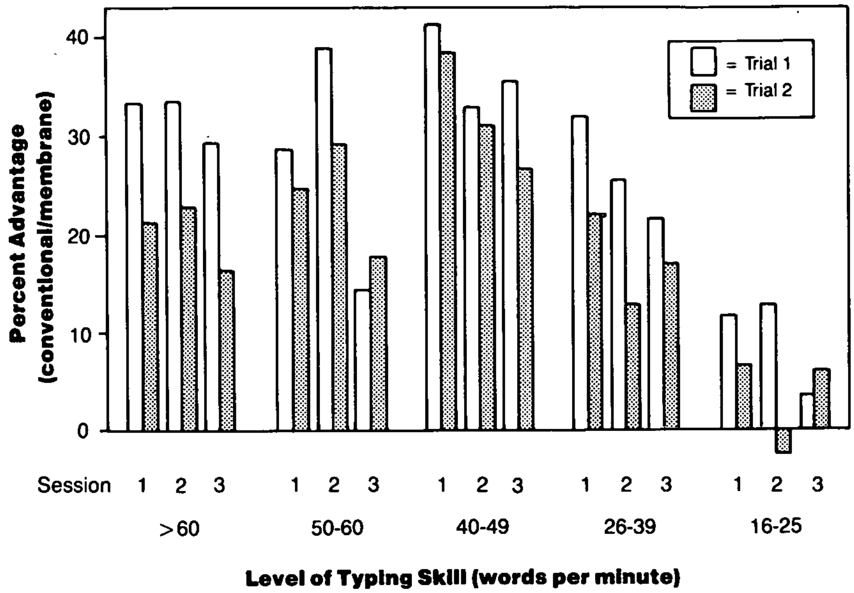

Figure 1. Average words-per-minute advantage of conventional over membrane keyboard as a function of typing skill and practice. (From Ref. 1)

Key Terms

Keyboards; membrane keyboard; touch typing; typing; typing speed

General Description

Results indicate little difference in performance between membrane and conventional keyboards for non-touch typists. For touch typists at all skill levels, better performance is demonstrated with the conventional rather than the membrane keyboard; however, these differences are substantially reduced with practice.

Methods

Test Conditions

- Conventional keyboard: 2.54 mm to key contact and additional 50 mm to end of key travel, 68-g average actuation force, 11.4-mm keytop diameter, 1.91-cm center-to-center interkey spacing, audible click for each keystroke
- Membrane keyboard: virtually no key travel, 82-g average actuation force, 1.52-cm keytop diameter, 1.91-cm center-to-center interkey spacing, audio tone for each keystroke
- Both keyboards: QWERTY layout and DELETE key for corrections, interfaced with MINC-11/03 minicomputer; output displayed on 22.86-cm video monitor placed in front of subject and behind keyboard; monitor displayed prompts (e.g., "type text") and the characters input by subjects
- Stimulus materials: six lists of 30 seven-digit numbers, two lists for each of three sessions per keyboard type, for dialing task; six paragraphs of text from standard typing textbook, each paragraph equated for typing difficulty; two paragraphs for each of three sessions per keyboard, for text typing task; materials used for dialing and text tasks identical for both keyboards; 12 different sets of general topic questions, two sets for each of three sessions, different but comparable questions asked for each keyboard type, for keyboard entry practice; materials mounted on stand to right of keyboard
- Typing skill levels: excellent (> 60 words per min [WPM]), good (50-60 WPM), fair (40-49 WPM), poor (26-39 WPM), nontouch (16-25 WPM)

Experimental Procedure

- Repeated measures design, keyboards counterbalanced within each skill level (except for non-touch typists)
- Independent variables: keyboard type, typing skill
- Dependent variables: dialing error (percentage of incorrectly entered and uncorrected phone numbers), average number of words typed during text task; average number of words typed in error divided by total typing in minutes performance difference between keyboards for text task (defined as number of words typed minus number of words typed in error divided by WPM on conventional keyboard × 100)
- Subject's task: type numbers (dialing task), type text, answer questions, type text, type numbers
- 21 subjects, 17 females and 4 males, Bell Telephone employees or community volunteers

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- No significant differences are found in accuracy for the dialing task for different keyboard types and typing groups.
- No significant differences are found in the average number of errors committed during the text task for the various keyboard types and typing groups; there is a significant effect ($p < 0.0005$) on errors due to trial number, with errors declining with practice.
- Significantly more ($p < 0.05$) error corrections are made with the membrane keyboard during the "text" task than with the conventional keyboard; significantly more ($p < 0.05$) error corrections are made in the second and third sessions than in the first session; there is a significant interaction ($p < 0.05$) between keyboards and trials, due to a larger practice effect for the membrane keyboard.
- There are significant differences ($p < 0.002$) in text typing speed for typing groups (i.e., better typists typed faster on both keyboards); text typing is significantly faster ($p < 0.005$) with the conventional rather than with the membrane keyboard.
- There is a significant improvement in text typing speed both across sessions ($p < 0.05$) and between trials within a session ($p < 0.005$), the latter due primarily to greater improvement with the membrane keyboard; there is a significant interaction ($p < 0.05$) between trial and session, due to a larger practice effect between trials during the first two sessions than during the last session.
- Post-hoc analysis indicates that the difference in text typing speed between the keyboards for the fair touch typist is reliably greater ($p < 0.05$) than for all other groups except the poor touch typists.
- Word-per-minute (WPM) scores show significant main effects ($p < 0.005$) for typing group, keyboard type, session, and trial; practice improves performance both across sessions and between trials; poor and nontouch typing groups differ reliably from other groups; performance is significantly better with the conventional keyboard than with the membrane keyboard, but only for excellent, good, and fair touch typists. The trials interact significantly ($p < 0.003$) with the keyboards and with sessions ($p < 0.05$); improvement across trials is greater with the membrane keyboard than with the conventional keyboard and the degree of improvement between trials within a session diminishes as the number of sessions increases.
- The percentage difference in WPM scores between the two keyboards shows significant main effects for session ($p < 0.04$) and trial ($p < 0.001$): both session and trial effects reflect a decrease in differences between keyboards with practice; the main effect of typing group approaches significance ($p < 0.054$), with the conventional keyboard showing little advantage over the membrane keyboard for the nontouch typist group, but a more pronounced advantage for the touch-typing groups; this advantage for the latter group is substantially reduced as a function of practice.

Variability

No information on variability was given.

Constraints

- Due to post-hoc assignment of subjects to typing groups, the counterbalancing for keyboard order was imperfect: unequal numbers of subjects appeared in each touch-typist group and no counterbalancing occurred for the nontouch typist group.
- The six text passages, although equated for difficulty based on syllabic intensity level, varied somewhat in the total number of words in each. This may have affected speed and accuracy results for the text task.

Key References

*1. Loeb, K. M. C. (1983). Membrane keyboards and human performance. *The Bell System Technical Journal*, *62*, 1733-1749.

Cross References

12.406 Numeric keyset arrangements: effects on speed and accuracy of data entry;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.409 Keyboard slope: effect on keying performance;

12.410 Keyboards and keysets: effects of key size, force, displacement, and feedback on keying performance;

12.414 Selection of data entry devices: rotary selectors, thumbwheels, and pushbuttons;

12.415 Selection of data entry devices: ten-button keyset, matrix keyboard, vertical levers, and rotary selectors

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12.408 Alphabetic Versus QWERTY Keyboard Arrangements

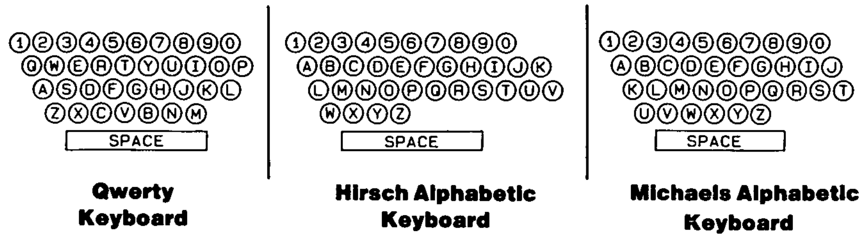

Figure 1. QWERTY keyboard and two alphabetic arrangements studied. (From Refs. 1, 2)

Key Terms

Alphabetic keyboard; Hirsch alphabetic keyboard; keyboard arrangement; Michaels alphabetic keyboard; QWERTY keyboard; typing

General Description

Table 1 summarizes two similar studies which compare keying performance as a function of keyboard arrangement. In Ref. 1, subjects had minimal typing experience. In Ref. 2, subjects at various skill levels were evaluated. The input material was similar in both studies, consisting mainly of names and telephone numbers. However, slightly different performance measures are used in each study. In the Hirsch study (Ref. 1), keying rate (adjusted for errors) is used, while in the Michaels study (Ref. 2), much more detailed measures are used. These consist of total work output (total data correctly input), alphabetic and numeric keying rate (key strokes per sec), and alphabetic and numeric error rate (ratio of errors to total keystrokes).

The findings from the studies are quite similar. In the Hirsch study, the keying performance of the alphabetic group, even after ~7 hr of practice, does not quite match their pretest performance on the QWERTY keyboard. In the Michaels study, work output is higher (significantly higher for high- and medium-skill typists) with the QWERTY than with the alphabetic keyboard for all groups. Alphabetic and numeric keying rates are also higher with the QWERTY keyboard than the alphabetic keyboard for all groups; however, not all differences are significant. Differences in alphabetic keying rate between keyboards are not significant for all groups; however, numeric error rates are lower (significantly lower for low- and medium-skill typists) with the alphabetic keyboard for all groups. Since numeric key arrangement is identical on the two keyboards, the advantage for the alphabetic keyboard is probably due to the general slowing effect it has on keying rate.

The general finding from the two studies is that the alphabetic keyboard shows no advantage over the QWERTY keyboard for the majority of typists. The performance of skilled typists is particularly hampered by the alphabetic arrangement. For very low-skill typists, the performance decrements associated with the alphabetic keyboard are less marked, but are still fairly substantial. A study by Norman and Fisher (Ref. 3) supports these findings. In this study, non-typists are used and textual material is input. Here, too, performance is significantly better with the QWERTY keyboard than with the alphabetic keyboard.

Constraints

• The input material used in these studies had letters and letter combinations which approximated the frequency-of-use considered in the design of QWERTY keyboard. Where abbreviated words or letter designators not fulfilling this requirement are used, different performance might be obtained.

Key References

*1. Hirsch, R. S. (1970). Effect of standard versus alphabetical keyboard formats on typing performance. *Journal of Applied Psychology, 54*, 484-490.

*2. Michaels, S. E. (1971). QWERTY versus alphabetic keyboards as a function of typing skills. *Human Factors, 13*, 419-426.

3. Norman, D. A., & Fisher, D. (1982). Why alphabetic keyboards are not easy to use: Keyboard layout doesn't much matter. *Human Factors, 24*, 509-519.

Cross References

12.406 Numeric keyset arrangements: effects on speed and accuracy of data entry;

12.407 Conventional versus membrane keyboards;

12.409 Keyboard slope: effect on keying performance;

12.410 Keyboards and keysets: effects of key size, force, displacement, and feedback on keying performance;

12.414 Selection of data entry devices: rotary selectors, thumbwheels, and pushbuttons;

12.415 Selection of data entry devices: ten-button keyset, matrix keyboard, vertical levers, and rotary selectors

Table 1. Summary of two studies investigating the effect of keyboard arrangement on performance.

Study	Subjects	Experimental Procedure	Experimental Results
Ref. 1	• 40 non-typists • College students • Selected on basis of pretest score on QWERTY as non-typists (25 words/min or less)	• Completely randomized design • Trials: practiced on keyboard for 50 min, then tested for 10 min • Seven trials per subject • Independent variable: QWERTY or alphabetic keyboard • Dependent variable: typing performance measured by keying input rate adjusted for errors	• QWERTY subjects show somewhat improved performance by Test 1, but the difference is not significant • Alphabetic subjects show significantly *poorer* performance on Test 1 than on the pretest ($p<0.001$) • By Test 7, the QWERTY subjects show significant improvement over their pretest performance ($p<0.01$) • By Test 7, the alphabetic subjects still do not equal their pretest performance on the QWERTY, but the differences are not significant
Ref. 2	• 30 subjects, male and female, ages 17-60 • Equal numbers of subjects assigned to low-, medium-, or high-skill groups on basis of professed typing proficiency	• Random block design • Half of each group started on the QWERTY keyboard and half started on the alphabetic • Subjects switched to the other keyboard after five trials • Trials: typed for 5 min, rested for 1 min while receiving feedback on performance, repeated sequence five times • 10 trials per subject, five on each keyboard • Independent variable: QWERTY or alphabetic keyboard • Dependent variable: typing performance measured by total work output, keying and error rates	• For high-skill typists, output is twice as high on the QWERTY as on the alphabetic keyboard • For medium-skill typists, output is 1.5 times as high on the QWERTY as on the alphabetic keyboard • For low-skill typists, output is higher on the QWERTY, but the differences are not significant • Both high- and medium-skill typists' alphabetic keying rate is significantly faster on the QWERTY than on the alphabetic keyboard ($p<0.001$) • Low-skill typists have faster alphabetic keying rates on the QWERTY, but the differences are not significant • Differences on alphabetic error rate are not significant for any skill level • High-skill typists' numeric keying rate is significantly higher on the QWERTY than on the alphabetic keyboard ($p<0.05$) • Both medium- and low-skill typists have faster numeric keying rates on the QWERTY, but the differences are not significant • For both low- and medium-skill typists, numeric error rates are significantly lower on the alphabetic than on the QWERTY keyboard ($p<0.01$) • For high-skill typists, numeric rate is also lower on the alphabetic keyboard, but this difference is not significant

12.409 Keyboard Slope: Effect on Keying Performance

Table 1. Effect of keyboard slope on keying performance.

Source	Slope Values (deg)	Results
Ref. 3	9, 21, 33	No significant effect on performance
Ref. 4	5, 10, 15, 25	No significant effect on performance
Ref. 2	5, 12, 18	Significantly better performance ($p < 0.05$) in terms of throughput and free-keying rate is obtained with the 12- and 18-deg keyboard slopes

Throughput = effective keystrokes per total time

Effective keystrokes (EKS) = total keystrokes − (error corrections + "backspace" or "word backspace" keystrokes)

Free-keying rate = EKS / (total time − wasted time)

Wasted time = time to key cursor positioning keystrokes (i.e., "backspace" or "word backspace") + keying time to replace characters

Key Terms

Keyboard preferences; keyboard slope; keying performance

General Description

Results indicate that keyboard slope has little influence on keying performance within the ranges tested. It appears that a keyboard slope that falls within the range of 10-35 deg should be acceptable for most applications (Ref. 1). To accommodate user preference as well as anthropometric limitations, however, slope should be adjustable where possible.

Constraints

- In Ref. 4, a thick-profile keyboard was used for the 15-deg slope condition, while low-profile keyboards were used for the other conditions.
- All studies used CRT screens and experienced typists.
- The height of the home row of keys is correlated with the keyboard slope in Ref. 2 such that the 5-, 12-, and 18-deg slopes correspond to 30, 38, and 45 mm respectively above the work surface. Both height and slope varied, i.e., results possibly depended on both.

Key References

1. Alden, D. G., Daniels, R. W., & Kanarick, A. F. (1972). Keyboard design and operation: A review of the major issues. *Human Factors, 14*, 275-293.

*2. Emmon, W. H., & Hirsch, R. S. (1982). Thirty millimeter keyboards: How good are they? *Proceedings of the 26th Annual Meeting of the Human Factors Society* (pp. 425-429). Seattle, WA: The Human Factors Society.

*3. Galitz, W. O. (1965, March). *CRT keyboard human factors evaluation*. Roseville: UNIVAC, Systems Application Engineering.

*4. Suther, T. W. III, & McLyre, J. H. (1982). Effect of operator performance at thin profile keyboard slopes of 5°, 10°, 15° and 25°. *Proceedings of the 26th Annual Meeting of the Human Factors Society*, (pp. 430-433). Seattle, WA: The Human Factors Society.

Cross References

12.304 Military aviator reach envelopes for placement of controls;

12.406 Numeric keyset arrangements: effects on speed and accuracy of data entry;

12.407 Conventional versus membrane keyboards;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.410 Keyboards and keysets: effects of key size, force, displacement, and feedback on keying performance;

12.414 Selection of data entry devices: rotary selectors, thumbwheels, and pushbuttons;

12.415 Selection of data entry devices: ten-button keyset, matrix keyboard, vertical levers, and rotary selectors

Notes

12.410 Keyboards and Keysets: Effects of Key Size, Force, Displacement, and Feedback on Keying Performance

Table 1. Effect of key size on keying speed and error rate.

Source	Key Sizes (cm)	Results
Ref. 2	0.95 x 0.95 1.27 x 1.27	Keying speed is significantly faster and error rate significantly lower with the 1.27 x 1.27 cm key

Key Terms

Key displacement; key size; keyboard feedback; keyboards; keying performance; keysets

General Description

The fastest keying speed and lowest error rate are found with a square 1.27-cm diameter key. However, this finding is based on a single study and some constraints exist, as indicated below. Within fairly wide limits (25.5-150.3 gm and 0.13-0.64 cm), force and displacement have little effect on performance. However, in general, low force and low displacement values are preferred for most applications. Additional feedback (e.g., tones, clicks, etc.) for key depression has not been found to significantly improve performance. In some cases (e.g., Ref. 3) it has been shown to degrade performance.

Constraints

- Reference 3 used experienced typists and a full QWERTY keyboard, while the other studies used ten-button telephone style keysets and relatively naive subjects.
- Reference 2 simultaneously varied both keys and character size; hence, it is not possible to determine cause for any differences in results.
- Where high vibration levels are expected, key force may need to be increased to prevent inadvertent keying.

Table 2. Effect of key resistance and travel on keying speed and accuracy.

Source	Force (g)/ Displacement (cm)	Results
Ref. 2	100/0.16 400/0.16 100/0.08 100/0.32 100/0.48	There are no significant differences in keying speed or error rate between any of the force/displacement conditions tested
Ref. 3	170/0.51 40/0.16 103/0.64 197/0.64 161/0.16	There are significant differences ($p < 0.01$) between keying speeds, error rates, and throughput (speed minus error) as a function of both force and displacement. The relative ranking (on throughput) of the conditions tested is shown by the listing at left. In general, the highest throughput is found when both force and displacement are relatively low in value

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Table 3. Effect of feedback on keying speed and accuracy.

Source	Type of Feedback	Results
Ref. 2	Auditory: tone Kinesthetic: snap of key action	There are no significant differences in keying speed or error rate when either type of feedback is added
Ref. 3	Kinesthetic: snap of key action	There is no significant effect on keying speed when feedback is provided; feedback significantly increases errors
Ref. 4	Auditory: single tone, multi-frequency tones, and clicks	There are no significant effects on keying speed or error rate when feedback is provided

Key References

1. Alden, D. G., Daniels, R. W., & Kanarick, A. F. (1972). Keyboard design and operation. A review of the major issues. *Human Factors, 14*, 275-293.

*2. Deininger, R. L. (1960). Human factors engineering studies of the design and use of pushbutton telephone sets. *The Bell System Technical Journal, 39*, 995-1012.

*3. Kinkead, R. D., & Gonzalez, B. K. (1969, March). *Human factors design recommendations for touch-operated keyboards - final report* (Document No. 12091-FR). Minneapolis, MN: Honeywell, Inc.

*4. Polard, D., & Cooper, M. B. (1979). The effect of feedback on keying performance. *Applied Ergonomics, 10*, 194-200.

Cross References

12.406 Numeric keyset arrangements: effects on speed and accuracy of data entry;

12.407 Conventional versus membrane keyboards;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.409 Keyboard slope: effect on keying performance;

12.414 Selection of data entry devices: rotary selectors, thumbwheels, and pushbuttons;

12.415 Selection of data entry devices: ten-button keyset, matrix keyboard, vertical levers, and rotary selectors

12.411 Multifunction Keyboards: Design Considerations

Key Terms

Computer-driven controls; control accessibility; control coding; control feedback; control placement; control/display placement; keyboard feedback; multifunction keyboards; programmable keyboards

General Description

Computer-driven control/display panels can be used to reduce the amount of dedicated panel space required in the cockpit by time-sharing the information presented and the control options available at any given time. For example, instead of using a dozen dedicated switches corresponding to 12 control functions, a smaller number, perhaps four or five, could be used. Each of these would control several different functions, with the particular one being active depending on what control function is most likely to be exercised during a particular operating mode (e.g., bombing, cruising, etc.). The following general guidance is offered on relevant design features that should be addressed when developing a multifunction control panel.

Identify Functions to Implement on a Multifunction Control

a. Conduct systematic task analysis to identify operator information and control requirements.
b. Assign critical (e.g., emergency) functions to dedicated controls.
c. Identify functions that could be efficiently operated via multifunction controls.

Maximize Accessibility of Frequently Used Functions

a. Organization by system may require logic steps. This should be avoided for frequently used functions (e.g., UHF radio channel changes).
b. Organization by flight mode (e.g., take-off, cruising, etc.) may eliminate some steps and is more appropriate for frequently used functions.
c. Steps may be reduced by programming logic to return to highest level of current operating modes when task is completed, after a suitable time delay (e.g., 10 sec).

Optimize Switch/Function Position Assignment

a. Base switch assignment on frequency of operation, required operating speed, and system-operations importance; high-scoring functions should have favored accessibility (e.g., top row of a column of switches).
b. Be consistent in location. Same function should appear in same relative location if used in multiple display pages or different control panels.
c. Group related functions together.

Minimize Hand Motion during Multifunction Control Operation

a. Sequential operations should, if possible, require repeated operations of the same switch (e.g., push once to access radio functions, again to select channel change function).
b. Where the above scheme is not possible, locate functions such that frequently used sequences can be carried out in a smooth left to right or top to bottom fashion.

Use Information Legends to Identify Switch Functions

a. Legends should unambiguously describe the functions they control (e.g., activate, increase, etc.).
b. Avoid abbreviations whenever possible, but when used, select clearly identifiable ones and apply them consistently.

Ensure Unambiguous Switch/Legend Association

a. Where possible, display legends on switch faces.
b. Next best is to place legends adjacent to switches, but aligned for the appropriate operator viewing angle and seat adjustment.

Eliminate Error-Prone Design Features

a. During digit entry, each selected number should be displayed on or near the control panel.
b. Current data entry should be displayed until the first digit of the new entry is selected; then each new digit is displayed as entered.
c. If the new selections are cleared before ENTER function is selected, current digits reappear.
d. Confirmation that a switch is active and that selection is acknowledged can be indicated by visual (e.g., color or intensity change, field reversal, symbology, etc.), auditory (click or tone), or kinesthetic (snap feel) feedback.
e. Programming should permit the operator maximum flexibility and ease of operation: allow operator to independently set system parameters; not require inputting of leading zeros or unnecessary symbols (e.g., deg, min, etc.), or special alignment of decimal points.

Implement Automatic Verification of Selections

a. System-detected errors should initiate a message specifying the error and the required remedial action.
b. Some types of verification: selection valid, data selection correct in length and format, number of selections sufficient for an operation, selection logically consistent with other selections.

Provide Efficient Correction Mechanisms

a. Back-stepping mechanism should be provided to allow quick return to previous page or the first page in a series.
b. CLEAR switch should be provided for easy correction of digital entry errors (e.g., one push clears last digit, two clear entire entry).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Although this guidance is based on over 7 yrs of research, it is neither definitive nor exhaustive. The designer is therefore cautioned to use it as initial specification and to refine the design, as necessary, through careful evaluation of the specific design application.

Key References

1. Calhoun, G. L., & Herron, E. L. (1982). Pilot-machine interface considerations for advanced aircraft avionics systems. *Advisory Group for Aerospace Research & Development Conference Proceedings* (AGARD-CP-329, pp. 24-1 to 24-7). London: Technical Editing and Reproduction Ltd.

Cross References

12.101 Recommended uses of controls;

12.102 Comparison of common controls;

12.301 Principles for grouping and arranging controls;

12.423 CRT touch screen devices

12.412 Control Type, Location, and Turbulence: Effect on Data Entry Performance

Table 1. Summary of selected experiments investigating the effects of control characteristics on data entry performance.

Experiment Number	Independent Variables	Results
1	1. Control type: a. dual concentric rotary selector b. two separate rotary selectors c. ten-button keyset 2. Location: five cockpit locations 3. Hand: right- or left-handed operation	Performance with the keyset is significantly faster than with the other controls ($p < 0.05$) Differences in speed due to location are too small for practical significance Differences in speed due to hand used are too small for practical significance No significant differences in error rate for any condition
2	1. Control type: a. dual concentric rotary selector b. ten-button keyset c. five-wheel discrete thumbwheel- 2. Time: practice effects	Differences in response times between the controls are significant, with the keyset the fastest and the thumbwheel the slowest All response times decrease significantly with practice, but there are no control type-by-practice interactions No significant differences are found in error rate for any condition
3	1. Keyset pressure: a. 2.24 N b. 4.48 N c. 4.92 N 2. Location: two cockpit locations 3. Turbulence: independent lateral and vertical movement of ± 2.54 cm (1 in.) for all trials	No significant differences in response time are found for any condition There is a consistent, though nonsignificant, reduction in errors as keyset pressure is increased Location has no consistent effect on error across conditions
4	1. Control type: a. ten-button keyset (4.92 N pressure) b. dual concentric rotary selector c. five-wheel discrete thumbwheel- 2. Location: two cockpit locations 3. Turbulence: independent lateral and vertical movement of ± 2.54 cm for one-half of trials 4. Occupations of subjects: pilots, electronics technicians	Differences in response time between controls are significant, with the keyset the fastest and the thumbwheel the slowest Turbulence results in significantly longer response times, but differences between controls in this respect are not significant Differences due to location are not of practical significance Response times for pilots are significantly shorter than for technicians Differences in error rates between controls are significant, with the keyset having the lowest error rate and the thumbwheel having the highest Error rates for pilots are generally lower than for technicians, but the differences are not statistically significant Error rates are generally higher with turbulence, but the differences are not consistently significant

Key Terms

Control placement; crew system design; discrete thumbwheel; keysets; rotary selector switches; turbulence

General Description

Across four experiments, data entry is consistently faster with a ten-button keyset than with rotary controls (both separate and concentric types), although these are slightly faster than thumbwheel controls. Higher error rates are found with the thumbwheel controls than with rotary controls. At 2.24 N key pressure, the ten-button keyset has higher error rates than the rotary controls; at 4.48 N key pressure, the keyset has an equal error rate, and at 4.92 N key pressure, the ten-button keyset has lower error rates than the rotary controls. Operation of the controls in five different cockpit locations has a very small effect on either response time or error rate. Simulated turbulence also has only small performance effects. Both with and without turbulence, shorter response times and lower error rates are found for the ten-button keyset with 4.92 N key pressure.

Constraints

- Different sized thumbwheel controls were used in Exps. 2 and 4.
- In Exp. 1, the ten-button keyset was located at the left side of the control panel, while in the other experiments it was on the right side.
- Since variation in control parameter may influence performance results, care should be taken in generalizing the results across different versions of the same type of controls.
- Most significance levels were not reported.

Key References

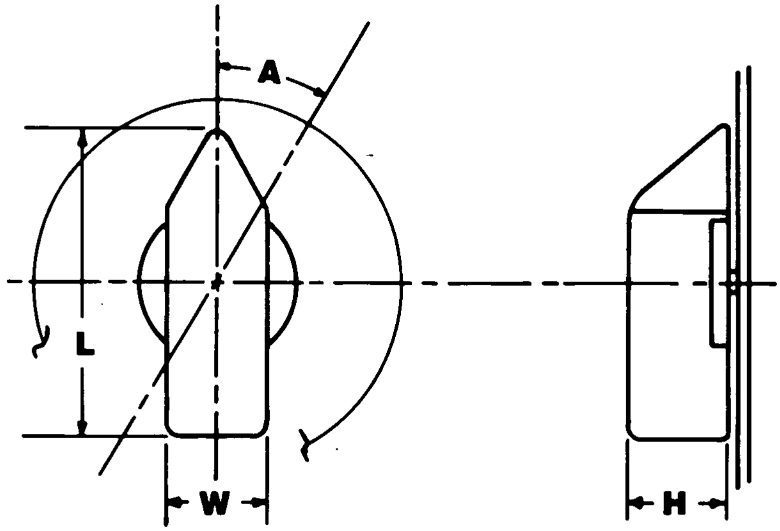
*1. Fenwich, C. A., & Hickok, C. W. (1975, April). *Keyboard data entry in avionics* (Rep. No. 750522). Wichita, KS: Society of Automotive Engineers.

Cross References

10.421 Model for predicting the effects of vibration on manual control performance;

10.424 Data entry performance during vibration

12.413 Rotary Selector Switches



	Length L	Width W	Depth H	Resistance
	Dimensions			
Minimum	25 mm (1 in.)		16 mm (0.625 in.)	113 mN-m (1 in.-lb)
Maximum	100 mm (4 in.)	25 mm (7 in.)	75 mm (3 in.)	678 mN-m (6 in.-lb)

	Displacement A: Regular*	Displacement A: Large**	Separation: One-Hand Random	Separation: Two-Hand Operation
Mimimum	15 deg	30 deg	25 mm (1 in.)	75 mm (3 in.)
Maximum	40 deg	90 deg		
Preferred	—	—	50 mm (2 in.)	125 mm (5 in.)

*For facilitating performance.
**When special engineering requirements demand large separation.

Figure 1. Rotary selector switch recommendations. (From Ref. 1)

Key Terms

Control placement; rotary selector switches; shape coding

General Description

Figure 1 gives specific design parameters for rotary selector switches. Table 1 delineates specific requirements pertinent to rotary selector switch design.

Constraints

- Specific applications may require some modifications in applying these design guidelines.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key References

*1. U.S. Army Missile Command (1981). *Human engineering design criteria for military systems, equipment and facilities* (MIL-STD-1472C). Philadelphia: Naval Publications and Forms Center.

Cross References

12.403 Legend switches;

12.419 Rotary controls: effect of knob shape on blind-positioning accuracy;

12.420 Ganged continuous rotary controls: minimum control dimensions

Table 1. Rotary selector switch design requirements. (Adapted from Ref. 1)

Scale/Pointer Requirements

- Moving pointer, fixed scale control used
- Control color/pointer references line contrast >75% under all lighting conditions
- Pointer mounted close to scale to minimize parallax

Positioning Requirements

- Control positions do not exceed 24
- Positions not placed opposite unless knob shape precludes directional confusion
- Stops provided at beginning and end of operating range
- Control snaps into position without stopping between positions

Control Shape Requirements

- Bar shape with parallel sides and pointed tapering index end
- Above requirement relaxed where shape coding required or space is limited and torque is light

12.414 Selection of Data Entry Devices: Rotary Selectors, Thumbwheels, and Pushbuttons

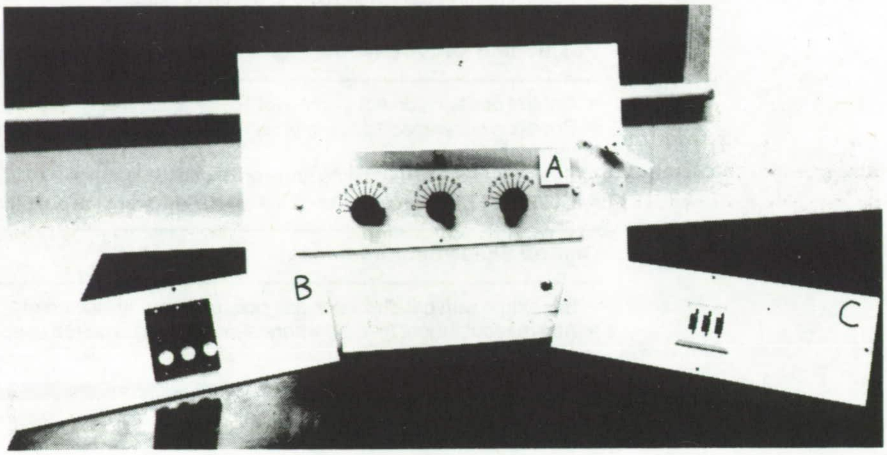


Figure 1. Control console and panels. (From Ref. 1)

Key Terms

Numeric data entry; positioning speed; pushbuttons; reading accuracy; rotary selector switches; thumbwheel switches

General Description

Data entry performance is affected by control type. Positioning performance is significantly faster with the rotary selector panel, but there are no significant differences in positioning errors among the panels. There are significantly more reading errors with the rotary selector panel.

Methods

Test Conditions

- Three interchangeable switch panels, mounted in 38.1 cm high x 50.8 cm wide control console; console mounted on work table 78.7 cm above floor and 40.6 cm from edge, inclined 15 deg from the vertical; panel and console light grey; Panel A contained three 10-position rotary selector switches with black numerals on a grey background, fixed scale and moving pointer; Panel B contained three 10-position digital pushbutton switches with white numerals on black background, each push advanced readout one digit; Panel C contained three 10-position digital thumbwheels with white numerals on black background; all numerals identical in size and design
- Subjects seated in front of console, 71.1 cm from panel surface
- Ten 3-digit numbers, typed one to a card, for each device for positioning task; ten 3-digit numbers on associated display of each panel for reading task

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variable: type of data entry device
- Dependent variables: positioning time (defined as time from subject's activation of timer until deactivation of timer), number of positioning errors, number of reading errors
- Subject's task: for positioning: read number on card, turn toggle ON (i.e., start timer), set switches, turn toggle OFF; for reading: turn toggle ON, read switch settings for 1 sec, orally report settings
- 12 male subjects, ages 25-48; 6 subjects for positioning and 6 for reading tasks

Experimental Results

- No significant differences in positioning errors between entry devices.
- Mean positioning time with the rotary switch panel is significantly shorter than for the pushbutton and thumbwheel switch panels.
- Significantly more reading errors are made with the rotary selector switch panel than with either the thumbwheel or pushbutton switch panels.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The authors report comparable results from a pilot study which duplicated this study. However, in the pilot study, positioning times for both the thumbwheel and rotary selector panels were superior to times obtained with the digital pushbutton panel. Slightly different thumbwheels were used in the two studies, and this might account for the performance differences. In addition, a higher percentage of reading errors was obtained with the rotary selector panel in the pilot study. The reduction shown in the current study is thought to be the result of using rotary selector hardware conforming to MIL-STD-1472C.

Constraints

• The large number of reading errors made with the rotary selector panel may be due in part to differences in hardware configuration: on both the thumbwheel and pushbutton panels, numerals are closely grouped and in line, while the rotary selector panel presented numerals in a 135-deg arc about switch centers and 15.3 cm apart; in addition, the rotary switch panel used black numerals on a grey background, while the other panels used white numerals on a black background.

Table 1. Reading errors and positioning time as a function of control type. (Adapted from Ref. 1)

Switch Type	Mean Positioning Time (seconds)	% Reading Errors	% Positioning Errors
Rotary selector	3.66	48	0
Thumbwheel	5.88	0	0
Pushbutton	6.44	0	1.66

Key References

*1. Plath, D. W., & Kolesnik, P. E. (1966). Readability and operability of three types of digital switches. *Journal of Engineering Psychology, 5*(2), 47-53.

2. U. S. Army Missile Command (1981). *Human engineering design criteria for military systems, equipment and facilities* (MIL-STD-1472C). Philadelphia: Naval Publications and Forms Center.

Cross References

12.406 Numeric keyset arrangements: effects on speed and accuracy of data entry;

12.407 Conventional versus membrane keyboards;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.409 Keyboard slope: effect on keying performance;

12.410 Keyboards and keysets: effects of key size, force, displacement, and feedback on keying performance;

12.415 Selection of data entry devices: ten-button keyset, matrix keyboard, vertical levers, and rotary selectors

12.415 Selection of Data Entry Devices: Ten-Button Keyset, Matrix Keyboard, Vertical Levers, and Rotary Selectors

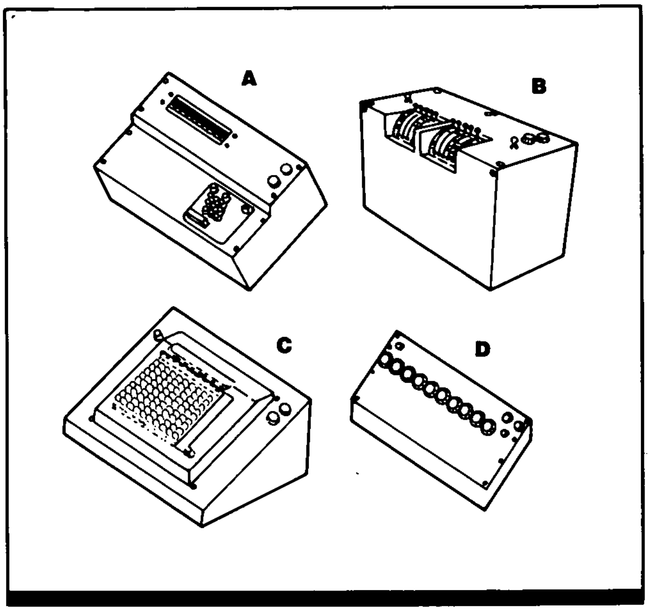


Figure 1. Input devices studied: A = ten-key keyboard, B = lever device, C = matrix keyboard, and D = rotary knob device. (From Ref. 1)

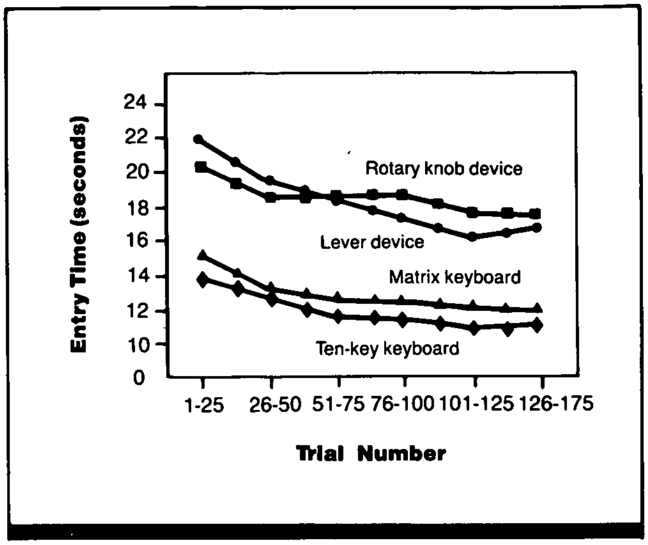


Figure 2. Average entry time as a function of entry device and number of trials. (From Ref. 1)

Key Terms

Keysets; matrix keyboard; numeric data entry; rotary selector switches; vertical levers

General Description

Significantly fewer data entry errors are made with the ten-button data entry keyset than with other devices studied. Both the ten-button keyset and the matrix keyboard require significantly less time per entry than either the vertical lever or rotary selector devices. A subjective ranking of the devices by subjects for accuracy and ease of operability shows a strong preference for the ten-button keyset.

Methods

Test Conditions

- Four data entry devices (Fig. 1), mounted 114 cm above floor, operated from standing position; each device had green "transmit" key for transference of data words into recording device, and red "in process" light to indicate that system is processing entry
- Ten-button keyset: "clear" key that erases entire entry; visual display
- Vertical lever device: ten levers and visual display, reposition lever for corrections; 9 x 10 numeric matrix keyboard, another key in column for corrections
- Rotary selector panel: horizontal row of ten switches, moving scales and fixed pointers, individual dial repositioned for corrections
- 700 data words, 175 per entry device, ten digits long, generated by subjects from master stimulus source cards (each with ten-digit data word from random number tables) via subtraction process

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variable: data entry device
- Dependent variables: time per entry (defined as time elapsed from indexing of first data word until depression of "transmit" key), error percent (defined as percent of transmitted entries containing one or more operator-caused, undetected indexing errors), operator entry device preference (on basis of accuracy and minimal difficulty or delay in use)
- Subject's task: read stimulus card, generate data word, enter data on device
- 24 male subjects, IBM machine and assembly workers, ages 23-56, no previous data entry experience

Experimental Results

- There is statistically significant ($p < 0.01$) overall difference in error rate among the four devices. Keying performance with the ten-button keyset is significantly more accurate ($p < 0.01$, $p < 0.05$, $p < 0.01$, respectively) than with the lever, matrix, or rotary selector devices, but the latter three devices do not differ significantly among themselves.
- There is a statistically significant difference ($p < 0.001$) in average entry time among the four devices. The ten-button keyset and the matrix keyboard require significantly less time per entry ($p < 0.01$) than the lever and rotary devices, but neither member of these pairs differs significantly from its mate.
- There is a significant overall difference ($p < 0.001$) in data entry times among the six sets of pooled trials (Fig. 2),

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

and a significant interaction ($p < 0.01$) between devices and trial sets.

- There is a significant overall difference ($p < 0.001$) in preference rating between devices.
- The ten-button keyset is significantly preferred ($p < 0.001$) over all other devices tested.
- The matrix keyboard is significantly preferred ($p < 0.01$) to either the lever or rotary selector device, but there are no significant differences in preference between the latter two devices.

Variability

No information on variability was given.

Constraints

- Design parameters for certain controls may have been suboptimal. For example, the tendency of subjects to overshoot control positions with the levers could have been reduced by increasing inertial resistance to provide improved damping action or by using detents.

Key References

*1. Minor, F. J., & Revesman, S. L. (1962). Evaluation of input devices for a data setting task. *Journal of Applied Psychology, 46*, 332-336.

Cross References

12.406 Numeric keyset arrangements: effects on speed and accuracy of data entry;

12.407 Conventional versus membrane keyboards;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.409 Keyboard slope: effect on keying performance;

12.410 Keyboards and keysets: effects of key size, force, displacement, and feedback on keying performance;

12.414 Selection of data entry devices: rotary selectors, thumbwheels, and pushbuttons

Table 1. Error rate and preference rankings for data entry devices. (Adapted from Ref. 1)

Device	Median Number of Erroneous Entries	Preference Ranking
Ten-button keyset	0.6	1
Vertical levers	2.3	3
Matrix keyboard	1.2	2
Rotary selectors	2.3	3

12.416 Rotary Controls: Spacing, Diameter, and Orientation

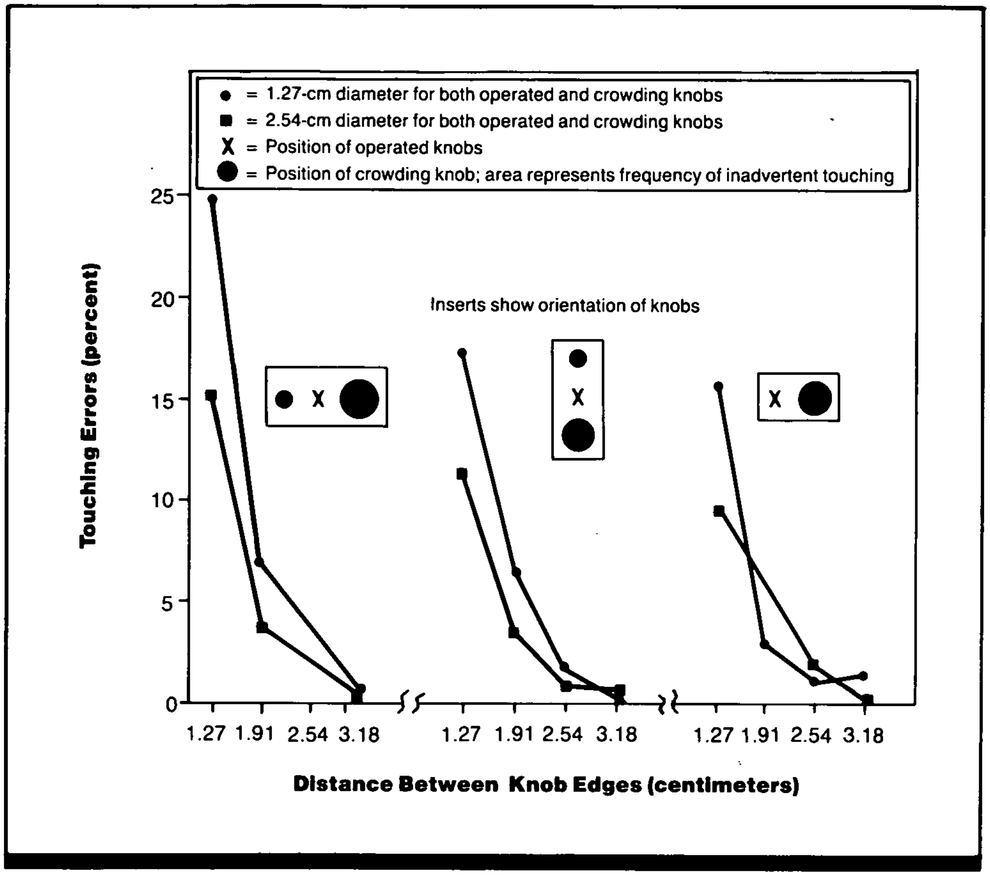


Figure 1. Error frequency as a function of knob diameter, orientation, and the distance between control edges. (From Ref. 1)

Key Terms

Control errors; control separation; rotary control spacing

General Description

Error rates decrease rapidly with increasing distance between control edges up to 2.54 cm, and improve rather slowly beyond this point. At equal distances between control centers fewer touching errors are made with the 1.27-cm diameter control than with larger controls. Thus when panel space is scarce, smaller diameter controls are preferred. Touching errors are less frequent when controls are in a vertical rather than a horizontal array. Controls to the right or below the operated control are more likely to be inadvertently touched than those above or to the left (right-handed operators).

Methods

Test Conditions

- Control mounted in center of 40.6 × 40.6 cm panel, flanked by other identical controls
- 1.27-cm diameter amber light mounted 6.03 cm above and 3.49 cm behind panel face; illuminated at start of trial, extinguished when center control positioned at 12 o'clock (± 1 deg)
- Telegraph key mounted 6.35 cm above lower edge and 14 cm in front of panel face; released by subject when amber light illuminated to start timing

Experimental Procedure

- Repeated measures designs, counterbalanced for order effects
- Independent variables: rotary control diameters (1.27 or 2.54 cm); control spacing(1.27-3.18 cm in 0.64-cm increments); vertical versus horizontal control arrays
- Dependent variables: reach time defined as elapsed time from subject's release of telegraph key until control knob turned; turning time defined as elapsed time from start of knob turn until light was extinguished; touching error defined as the inadvertent contact of subject's hand with adjacent controls
- Subject's task: release telegraph key, position control knob index to 12 o'clock without touching adjacent controls
- Adjacent controls (either above and below, or at right and left) were used
- 24 subjects, right-handed male college students

Experimental Results

- The main effects of spacing (S), diameter (D), and configuration (C), as well as the interactions between S and D and S and C are significant ($p < 0.05$) for all dependent variables.
- Performance improves as the distance between control knob edges is increased from 1.27-3.175 cm.
- Controls located to the right or below the operated control are more likely to be inadvertently touched than those above or to the left. Inadvertent touching is less frequent when controls are arranged in a vertical rather than a horizontal array.
- When comparisons are made at equal distances between control knob edges, performance improves with increasing knob diameter. However, when comparisons are made at equal distances between control centers, performance is more accurate for 1.27-cm diameter control knobs than for either 2.54- or 3.81-cm diameter control knobs.
- Results of Exp. 2 are shown in Figs. 1 and 2.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Another experiment (Ref. 1) testing only control spacing and control size also found these variables to have a significant effect on performance. Similar results were obtained by Bradley and Wallis (Ref. 2) when spacing, diameter, and orientation were examined for pushbutton controls.

Constraints

- The results should not be applied to discrete rotary selector controls.
- The results apply only to continuous rotary controls that can be operated by moderate torque.

Key References

*1. Bradley, J. V. (1969). Optimum knob crowding. *Human Factors, 11*, 227-238.

2. Bradley, J. V., & Wallis, R. A. (1958, April). *Spacing of on-off controls. 1: Pushbuttons* (WADC-TR-58-2). Wright-Patterson Air Force Base, OH: Wright Air Development Center.

Cross References

12.303 Recommended minimum distances between controls;

12.401 Pushbuttons: effects of spacing, diameter, and orientation on error rate;

12.404 Toggle switches: effects of spacing, orientation, and direction of throw on error rate;

12.413 Rotary selector switches;

12.419 Rotary controls: effect of knob shape on blind-positioning accuracy;

12.420 Ganged continuous rotary controls: minimum control dimensions

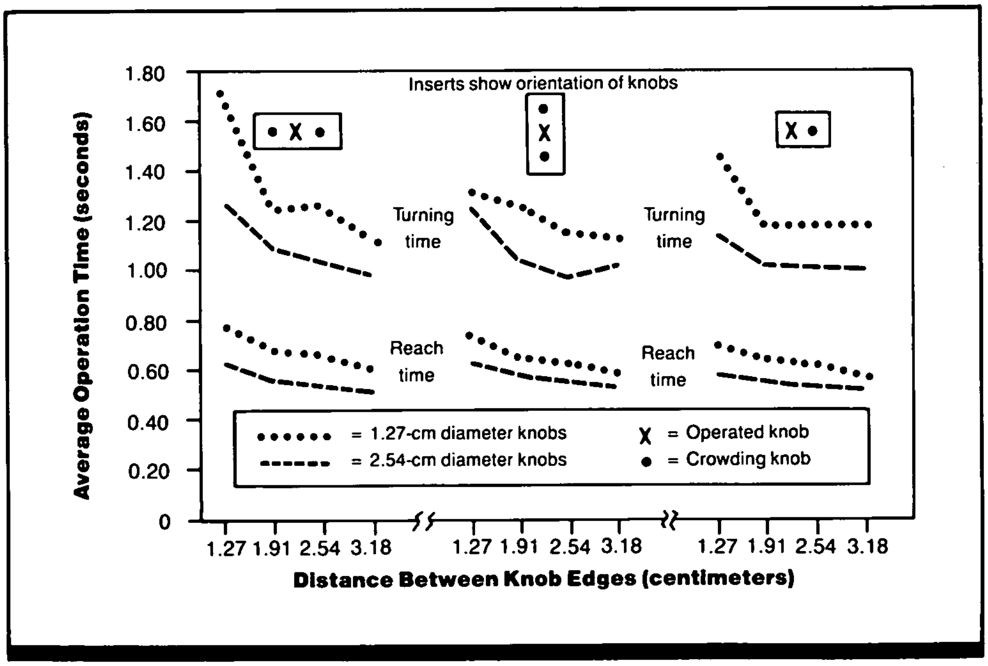


Figure 2. Operation time as a function of knob diameter, orientation, and the distance between control edges. (From Ref. 1)

12.417 Continuous Rotary Controls: Size Coding

Key Terms

Blind positioning; control size; rotary controls; tactual pattern discrimination

General Description

When continuous rotary control knobs differ in diameter by at least 1.27 cm, or differ in thickness by at least 0.95 cm, they are not easily confused. Both diameter and thickness could be used in conjunction with fluting or knurling of the rim surface to develop a very large coding set.

Methods

Test Conditions

- Subjects seated facing apparatus window where full-sized photos of two alphabetically labeled knobs appeared; curtained aperture through which subject reached to feel knob
- Experiment 1: seven 1.27-cm thick, smooth rimmed, cylindrical, aluminum-alloy knobs varying in diameter: a = 1.27, b = 1.59, c = 1.91, d = 2.22, f = 2.54, h = 2.86, j = 3.18 cm
- Experiment 2: five 2.54-cm diameter, smooth-rimmed, cylindrical, aluminum-alloy knobs varying in thickness: A = 0.95, B = 1.27, C = 1.59, D = 1.91, and E = 2.22 cm

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: Knob diameter, knob thickness
- Dependent variables: knob-confusability (defined as the number of times a knob is incorrectly named)
- Subject's task: reach through curtained aperture, feel knob, call out letter designation (from two photos shown) of felt knob
- No time constraint on subjects
- 21 right-handed male college students, well-practiced with task in Exp. 1; 20 right-handed male and female subjects, college students in Exp. 2

Table 1. Number of times an incorrect knob was called in Experiment 1. (From Ref. 1)

		Felt Knob							
		a	*b*	*c*	*d*	*f*	*h*	*j*	cm (in.)
Wrong Response	*a*	X	9*	3	1				1.27 (4/8)
	b		X	3	4	1			1.59 (5/8)
	c		1	X	10*	3			1.91 (6/8)
	d		1	1	X	3	2		2.22 (7/8)
	f				3	X	4	3	2.54 (8/8)
	h					1	X	4	2.86 (9/8)
	j						4	X	3.18 (10/8)
		1.27	1.59	1.91	2.22	2.54	2.86	3.18	

*Does *not* differ significantly at one-tailed .05 level from frequency expected by chance.
Maximum possible cell entry = 21.

Table 2. Percentage of misidentification trials as a function of the diameter difference between knobs compared in Experiment 1. (From Ref. 1)

Size of Alternative Relative to Felt Knob	Diameter Difference between Alternative and Felt Knobs in centimeters (inches)					
	0.32 (1/8)	**0.64 (2/8)**	**0.95 (3/8)**	**1.27 (4/8)**	**1.59 (5/8)**	**1.91 (6/8)**
Smaller	26.2	14.3	2.4	0	0	0
Larger	7.9	1.0	0	0	0	0

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Experimental Results

- Knobs differing in diameter by at least 1.27 cm are never confused.
- Knobs differing in thickness by at least 0.95 cm are never confused.
- The obtained percentage of errors at a given difference in thickness (or diameter) does not vary appreciably with the absolute thickness (or diameter) of the knob.

Variability

No information on variability was given.

Constraints

- Due to the somewhat artificial nature of the task (i.e., a dichotomous choice) the discriminability shown here is probably higher than would be seen in a real-life application.

Key References

*1. Bradley, J. V. (1967). Tactual coding of cylindrical knobs. *Human Factors*, *9*, 483-496.

Cross References

12.424 Control coding;

12.425 Push-button controls: shape coding

Table 3. Number of times an incorrect knob was called in Experiment 2. (From Ref. 1)

		Felt Knob A	B	C	D	E	cm (in.)
Wrong Response	*A*	X	2				0.95 (3/8)
	B	2	X		1		1.27 (4/8)
	C	1	7*	X			1.59 (5/8)
	D		4	5	X	1	1.91 (6/8)
	E			1	8*	X	2.22 (7/8)
		0.95	1.27	1.59	1.91	2.22	

* Does *not* differ significantly, at one-tailed .05 level from frequency expected by chance.
Maximum possible cell entry = 20.

Table 4. Percentage of misidentification trials as a function of the thickness difference between compared knobs in Experiment 2. (From Ref. 1)

Size of Alternative Relative to Felt Knob	Thickness Difference between Alternative and Felt Knob in centimeters (inches) 0.32 (1/8)	0.64 (2/8)	0.95 (3/8)	1.27 (4/8)
Smaller	3.8	1.7	0	0
Larger	27.5	10.0	0	0

12.418 Rotary Selector Controls: Shape Coding

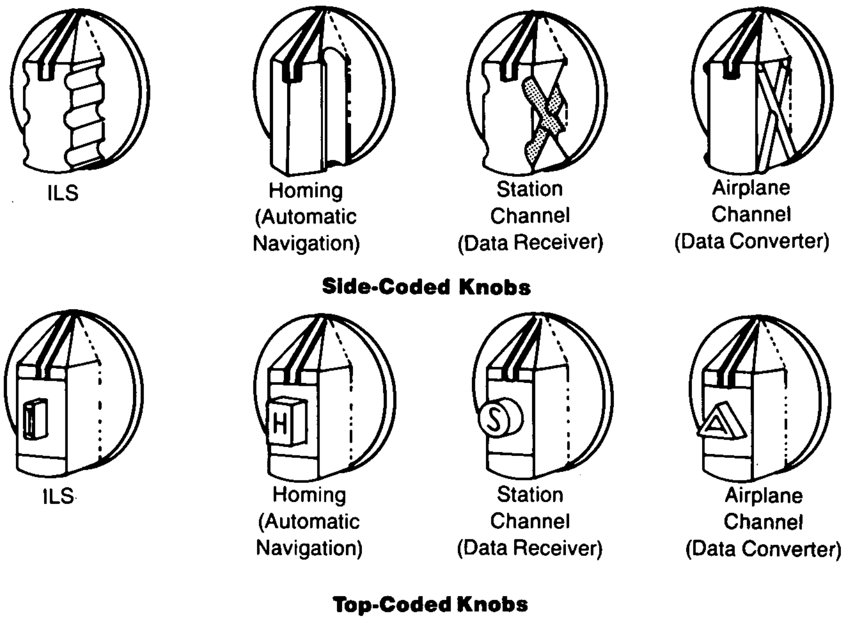


Figure 1. Shape-coded knobs. (From Ref. 1)

Key Terms

Blind positioning; information portrayal; rotary selector switches; shape coding; tactual pattern discrimination

General Description

Rotary selector controls with shape-coded tops used in this experiment are identifiable by touch essentially without error from the very first exposure, indicating that little or no learning is required for their use. With more abstractly coded (e.g., side coding used here) or non-coded rotary selector controls, an initial learning period is required before they can be operated without error. In terms of total operating time, there are no differences between coded and non-coded rotary selector controls.

Applications

The design of shape-coding strategies where rotary selector controls must be blindly positioned and errors are critical.

Methods

Test Conditions

- Three sets of four parallel slab-sided rotary selector controls; one set without coding, one set side-coded with grooves, and one set top-coded with geometric shapes (Fig. 1)
- Experiment conducted in F-106/MA1 cockpit simulator
- Subjects wore standard Air Force flight gloves under all conditions
- Each positioning instruction orally presented over intercom
- Subjects performed, with left hand, secondary tracking task that required full visual attention during experiment

Experimental Procedure

- Details lacking, but random-block design probably used
- Independent variable: coding method
- Dependent variables: total time (defined as travel time plus feeling time), travel time (defined as time from release of flight stick until correct switch touched), feeling time (defined as elapsed time from touching of correct control until its rotation); touching error (defined as the touch, but not rotation, of wrong control); turning error (defined as the rotation of wrong control)
- Subject's task: release right hand from flight stick, locate and position appropriate rotary selector control while maintaining visual attention and left-hand control of a secondary tracking task
- For non-coded controls, subjects instructed to count back to appropriate control; for coding controls, subjects instructed to reach directly to appropriate control, then feel control to confirm identity
- 12 subjects at three levels of experience: 3 professional test pilots, 3 non-pilots familiar with F-106 cockpit, 6 engineers and draft persons unfamiliar with panels

Experimental Results

- No turning errors were made with top-coded controls during the first 48 trials, and only one error was made during the second 48 trials.
- With both side-coded and non-coded controls, a wrong switch was turned at least twice by each subject during the first 48 trials.
- Very few errors were committed with any control during the second 48 trials (Fig. 2).
- Analysis of the data (no details given) indicated there were no significant differences in operation time between the controls (coded or non-coded).
- During the first 48 trials, touching errors were made on 32% of the trials; during the second 48 trials, touching errors were made on only 19% of the trials.

Variability

No information on variability was given.

Constraints

- Details of methodology, statistical analyses, and significance levels are lacking.
- Coding method confounded location of code (top or side) with manner of coding (raised or inset).
- Use of such coding involves added cost for manufacturing and replacement, and danger of interchange during maintenance.

Key References

*1. Slocum, G. K., & Hopkins, C. O. (1957, February). *An experimental evaluation of two types of shape-coded rotary switch knobs for aircraft cockpit applications*, (Rep. No. 4112.7/51). Hughes Aircraft Company, Culver City, CA, Radar Department.

Cross References

9.208 Blind positioning accuracy: effect of target location;

9.209 Restricted blind-positioning: effects of distance and direction;

12.417 Continuous rotary controls: size coding;

12.419 Rotary controls: effect of knob shape on blind-positioning accuracy;

12.424 Control coding;

12.425 Push-button controls: shape coding

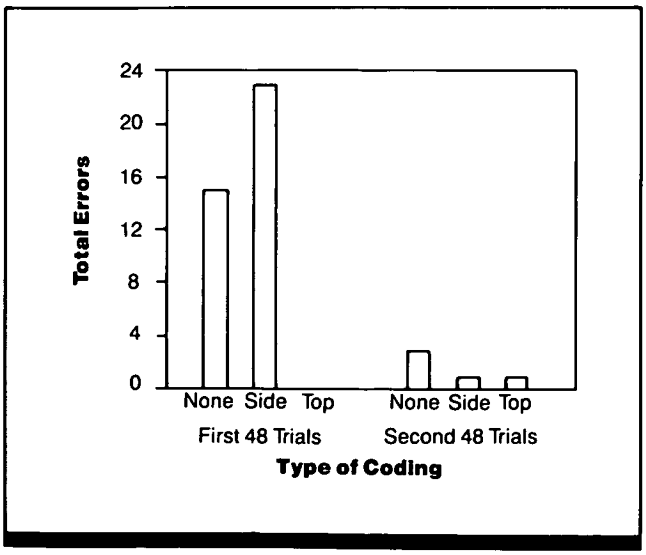


Figure 2. Error rate as a function of type of coding. (From Ref. 1)

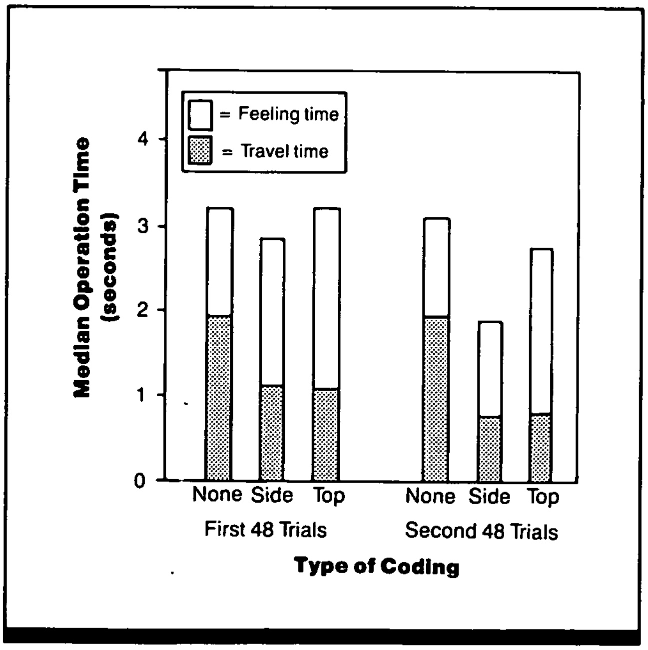


Figure 3. Median operation time as a function of type of coding. (From Ref. 1)

12.419 Rotary Controls: Effect of Knob Shape on Blind-Positioning Accuracy

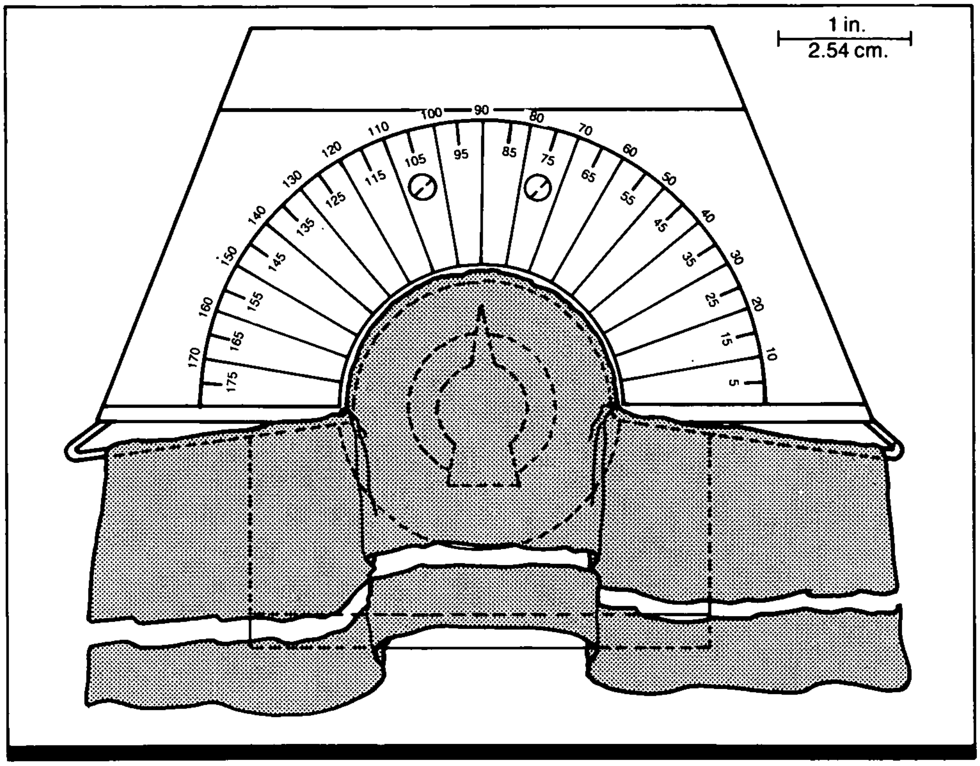


Figure 1. Front view of testing apparatus. Shaded portion indicates curtain-concealing control. (From Ref. 2)

Key Terms

Blind positioning; control shape; knob shape; positioning accuracy; rotary controls

General Description

The range of setting errors in ~28 deg for the tapered knob and ~22 deg for the parallel-sided knob. With the tapered knob, the average difference between right- and left-hand settings is 16 deg; with the parallel-sided knob the difference is <2 deg. In general, right-handed settings are more accurate between nine and twelve o'clock positions and left-handed settings are more accurate between twelve and three o'clock positions. For accuracy of blind positioning, the parallel-sided knob is superior to the tapered knob. For ease and accuracy, the spacing between discrete positions of the control should be 35 deg or more.

Applications

The design of rotary control knobs for environments where controls must be positioned without visual reference.

Methods

Test Conditions

- Two control knobs: one tapered knob, 3.81 cm long, 2.29 cm deep, with pointer portion forming 16-deg angle; one parallel-sided knob 3.81 cm long, 1.75 cm deep, 1.27 cm wide
- Knobs mounted on test panel (Fig. 1) and located 35.56 cm below eye level in front of and facing subject
- Panel positioned by subject to comfortable working location; unshaded portion of Fig. 1 visible to subject
- Fourteen angular positions used for settings; five settings each at 10, 30, 50, 70, 90, 110, 130, 150, or 170 deg and one setting each at 35, 65, 95, 125, or 155 deg

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: knob shape, hand used, position setting
- Dependent variables: mean setting, constant error, average error
- Subject's task: position control knob to indicated scale setting while holding knob between thumb and first and second fingers
- Subjects instructed to strive for accuracy rather than speed
- 4 subjects

Experimental Results

- Settings made with the right and left hands differ more when the tapered knob is used than when the parallel-sided knob is used (Fig. 2).
- Settings made with the tapered knob tend to be more counterclockwise with the left hand and more clockwise with the right hand than do settings made with the parallel-sided knob (Fig. 3).
- In general, settings made with the right hand are more precise from 90-170 deg and with the left hand from 10-90 deg (Fig. 4).

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

- Use of the tapered knob results in an average increase in setting error of 6.5 deg for the right-hand settings and 9.0 deg for the left, compared to the parallel-sided knob.
- When employing either knob, the widest range of errors occurs at the 50- and 110-deg positions and the narrowest at the 90-deg position for the parallel knob and at the 150-deg position for the tapered knob.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The differences in accuracy and direction of error for right- to left-hand settings are consistent with the findings of Chapanis (Ref. 1).

Constraints

- No statistical analyses reported.
- Small sample size used and no demographic data given.

Key References

1. Chapanis, A. (1951). Studies of manual rotary positioning movements: I. The precision of setting an indicator knob to various angular positions. *Journal of Psychology, 31*, 51-64.

*2. Hunt, D. P., & Warrick, M. J. (1975, March). *Accuracy of blind positioning of a rotary control* (WADC Technical Note 51-106). Wright-Patterson Air Force Base, OH: Wright Air Development Center. (DTIC No. AD142291)

Cross References

9.208 Blind positioning accuracy: effect of target location;

9.209 Restricted blind-positioning: effect of distance and direction;

12.413 Rotary selector switches;

12.420 Ganged continuous rotary controls: minimum control dimensions

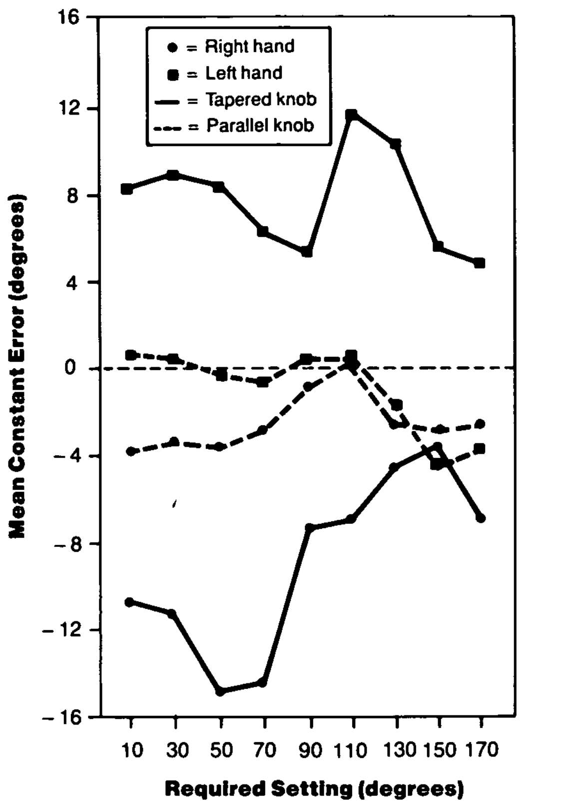


Figure 3. Mean constant error as a function of required setting. (From Ref. 2)

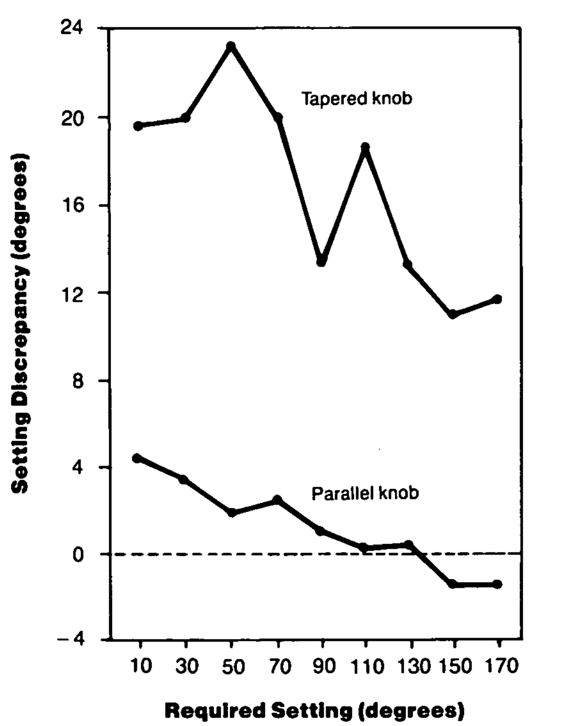


Figure 2. Mean setting discrepancy between right and left hands as a function of required setting for two types of control knobs. (From Ref. 2)

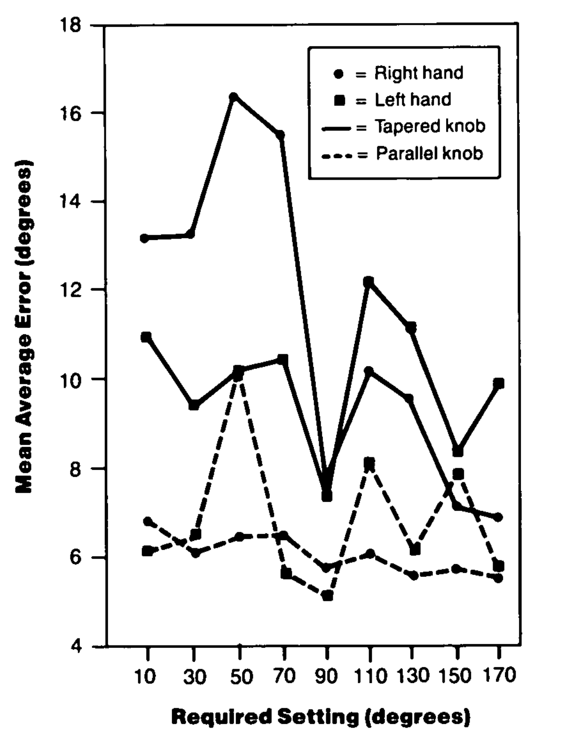


Figure 4. Mean average error as a function of required setting. (From Ref. 2)

12.420 Ganged Continuous Rotary Controls: Minimum Control Dimensions

Key Terms

Concentric controls; ganged continuous rotary controls; rotary controls; stacked controls

General Description

Concentric controls, knob diameter, thickness, and the differences in diameter between adjacent controls, can all affect reach time, turning accuracy, and touching errors. The results from a series of four experiments are incorporated into Fig. 1. They suggest minimum dimensions for the controls studied. When the avoidance of inadvertent operation of adjacent, non-detent controls is the critical design consideration, panel space will seldom be saved by the use of concentrically mounted controls due to the large diameter differences necessary between such controls.

Methods

Table 1 lists specific parameter values investigated

Test Conditions

- Three concentrically ganged control knobs mounted in center of panel; amber light (signaling trial start) mounted 5.72 cm above and 5.08 cm behind face of panel, extinguished when black index on operated knob was turned to 12 o'clock (± 1 deg); telegraph key mounted 2.54 cm above and 6.35 cm in front of panel, released at signal light
- Four experiments conducted;

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: control knob thickness, control knob diameter, difference in diameter between operated and adjacent control knobs
- Dependent variables: reach time (defined as time from release of telegraph key until operated knob begins to turn), turning time (defined as time from when operated knob begins to turn until knob index is at 12 o'clock), touching error (defined as the inadvertent touching of knob behind or knob in front of operated knob one or more times per trial)
- Subject's task: release telegraph key, grasp one of three ganged control knobs, and turn knob index to 12 o'clock (i.e., extinguish amber light) without touching adjacent controls
- 38 subjects, college students, 6-12 in each experiment, using dominant hand

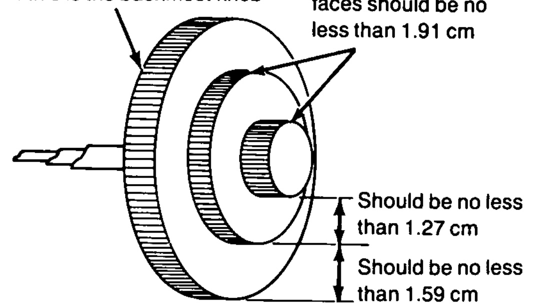


Figure 1. Recommended minimum dimensions for concentric controls when (a) middle knob diameter is between 3.81 and 6.35 cm; (b) knob is operable by moderate torque; and (c) frequent inadvertent adjacent knob operation is undesirable. (From Ref. 2)

Experimental Results

- When the middle knob (5.08 cm diameter) is operated, as the difference in diameter between the front and middle knob is decreased <2.54 cm, performance is greatly degraded, and front knob thickness between 1.27 and 2.54 cm has little influence on middle knob performance. The middle knob should be at least 1.91 cm thick.
- When the back knob is operated, as the diameter difference between the back and middle (5.08 cm diameter) knobs is decreased < 3.18 cm, performance is greatly degraded. When this diameter difference is < 2.54 cm, the back knob should be a minimum of 1.27 cm thick.
- Back knob errors are primarily sensitive to differences in their thickness.
- Front knob errors respond most dramatically to diameter difference.
- Reach time is sensitive to all main effects, although not always as sensitive to diameter differences as are front knob errors.
- Turning time is virtually insensitive to knob thickness and generally inferior to reach time in reflecting changes in the second manipulated variable (i.e., diameter).
- The large diameter differences necessary to prevent front knob errors suggest that where inadvertent operation of adjacent controls is a critical error, panel space will not be saved by mounting controls on concentric shafts.

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

Reference 1 confirms the finding that mounting controls on concentric shafts will not save panel space when the prevention of inadvertent operation of adjacent controls is of critical importance.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Constraints

- Because the probability of inadvertent operation of adjacent controls is inferred from the frequency of inadvertent touching, the results apply only to concentrically mounted continuous-rotary controls which can be operated by moderate torque.
- For the minimal tolerable dimension, the author's criterion was the point at which the time or error performance curve became nearly parallel to the x-axis.
- Situations where it may be appropriate to use concentrically mounted continuous rotary controls include (a) where control operations are sequentially or functionally related, (b) where neither inadvertent operation of adjacent control knobs nor small time delays are critical, (c) where large diameter knobs must be used whether knobs are ganged or isolated, (d) where it is necessary to save space behind the panel.

Key References

1. Bradley, J. V. (1957). Control knob arrangement can save aircraft instrument panel space. *Journal of Aviation Medicine, 28*, 322-327.

*2. Bradley, J. V. (1969). Desirable dimensions for concentric controls. *Human Factors, 11*, 213-226.

3. Bradley, J. V., & Stump, N. E. (1955, December). *Minimum allowable dimensions for controls mounted on concentric shafts* (WADC-TR-55-355). Wright-Patterson Air Force Base, OH: Wright Air Development Center. (DTIC No. AD093135)

Cross References

12.413 Rotary selector switches;

12.419 Rotary controls: effect of knob shape on blind-positioning accuracy

Table 1. Summary of parameters investigated in each experiment.

Experiment (Number of subjects)	Knob Operated	Parameter Values Investigated (in cm): Fixed	Parameter Values Investigated (in cm): Varied
1 (*n* = 8)	Front knob	Middle knob diameter: 22.86	Front knob diameter: 2.54, 5.08, 7.62, 10.16; thickness: 0.635, 1.27, 1.91, 2.54
2 (*n* = 6)	Middle knob	Middle knob diameter: 5.08 thickness: 1.27 Back knob diameter: 12.7 thickness: 2.54	Front knob thickness: 1.27, 1.91, 2.54 Front knob to middle knob diameter differences: 0.635, 1.27, 1.91, 2.54, 3.18, 3.81
3 (*n* = 12)	Middle knob	Front knob diameter: 1.27 Middle knob thickness: 5.08 Back knob diameter: 12.7 thickness: 2.54	Middle knob thickness: 1.27, 1.91, 2.54, 3.81 Front knob to middle knob diameter difference: 1.27, 1.91, 2.54, 3.18
4 (*n* = 12)	Back knob	Front knob diameter: 2.54 thickness: 1.91 Middle knob diameter: 5.08 thickness: 1.91	Back knob thickness: 0.635, 1.27, 1.91 Back knob to middle knob diameter difference: 1.27, 1.91, 2.54, 3.18, 3.81, 4.45

12.421 Joystick Type: Effect on Tracking Performance

Key Terms

Compensatory tracking; control order; displacement joystick; pressure joystick; pursuit eye movements; zero-order controls

General Description

With displacement joysticks, the output is proportional to the degree of displacement from the control's null position. With pressure or force joysticks, the control output is proportional to the amount of force applied to the control. In compensatory tracking, either the target or the controlled element of the display is fixed and the other one moves; the operator only knows the absolute error or difference between the two. In pursuit tracking, both display elements (i.e., target and controlled element) move, and the operator is presented with information about the actual location of each. Control order involves the relationship between control input and system response. For example, with zero-order controls, only position is controlled. With first-order controls, the velocity or rate of response is controlled and second-order controls involve acceleration control.

In the six studies listed below, the pressure joystick consistently provides smaller tracking error than the displacement joystick. This superiority appears valid for tasks involving zero-, first-, second-, and third-order controls and either pursuit or compensatory tracking tasks.

Constraints

- Various factors, such as stick dimensions and control/display ratio (gain) can affect tracking performance.
- The superiority of pressure joysticks may not extend to tasks other than tracking.

Key References

1. Birmingham, H. P. (1950). *Comparison of a pressure and moving joystick* (Interim Report S-3600-330A/50). Washington, DC: Naval Research Laboratory.

2. Burke, D., & Gibbs, C. N. (1965). A comparison of free-moving and pressure levers in a positional control system. *Ergonomics, 8,* 23-29.

3. Gibbs, C. B. (1952). *The advantages of a pressure-operated control lever in a velocity control system* (APU 161/51). Cambridge, England: Applied Psychology Research Unit, Medical Research Council.

4. Gibbs, C. B. (1962). The continuous regulation of skilled responses by kinesthetic feedback. *British Journal of Psychology, 45,* 24-39.

5. North, J. D., & Lomnicki, Z. A. (1961). Further experiments on human operators in compensatory tracking tasks. *Ergonomics, 4,* 339-353.

6. Zeigler, P. N., & Chernikoff, R. A. (1968). A comparison of three types of manual control on a third order tracking task. *Ergonomics, 11,* 369-374.

Cross References

10.422 Manual control performance: effect of system dynamics and vibration frequency;

12.422 Comparison of cursor control devices

Notes

12.422 Comparison of Cursor Control Devices

Input devices

1 = Touch screen: on the display screen, with an enter switch
2 = Touch screen: on the display screen, with no switch
3 = Light pen: with an enter switch
4 = Light pen: with no switch
5 = Data tablet: with an enter switch
6 = Touch screen: adjacent to the display, with an enter switch
7 = Trackball: with an enter switch
8 = Force joystick: with an enter switch
9 = Position joystick: with an enter switch
10 = Keyboard: with an enter switch

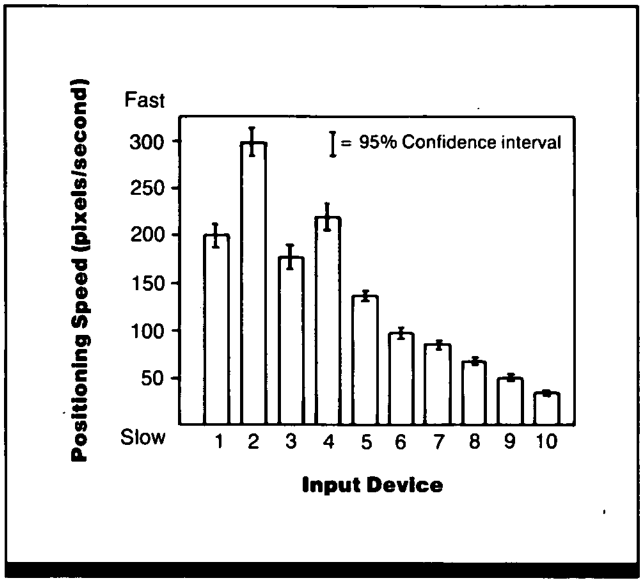


Figure 1. Mean positioning speed as a function of control device. (From Ref. 1)

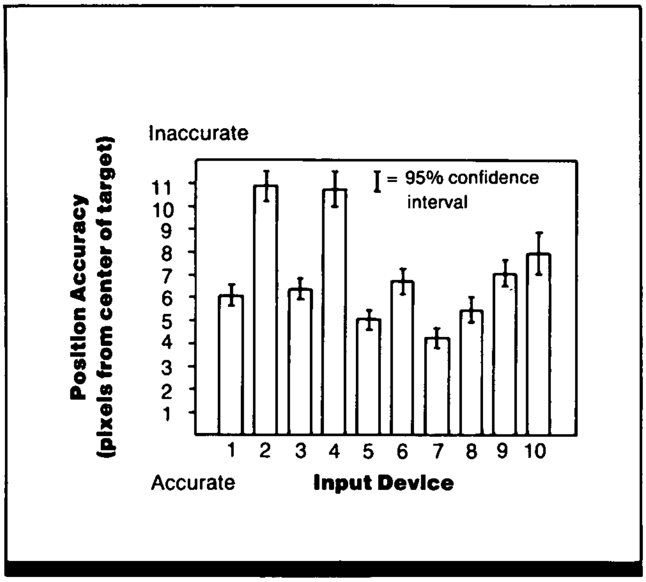


Figure 2. Mean positioning accuracy as a function of control device. (From Ref. 1)

Key Terms

Cursor control; data tablet, joysticks; light pens; touch screen; trackballs

General Description

Cursor positioning speed and accuracy depend on the input device used. The most accurate device of those tested is the trackball, while the least accurate device is the touch screen without the footswitch. The fastest device tested is the touch screen without the footswitch, and directional keys are the slowest. A speed/accuracy tradeoff is involved, with the least accurate device being the fastest and the most accurate being among the slowest. Most interactive systems involve several tasks which require varying degrees of speed or accuracy. The data can provide general guidance in considering tradeoffs.

Methods

Test Conditions

- Graphic display shown on 640 × 512 resolution 48.3-cm monitor; green target (65 × 65 pixels) on white cursor (1 × 32 pixels) on black background
- Control devices: (1) force joystick, (2) spring-centered displacement joystick, (3) 5.08-cm diameter trackball, (4) 28 × 28-cm tablet with coordinate indicating puck, (5) light pen, (6) eight directional keys (vertical, horizontal, and diagonal movement), (7) 1,000 × 1,000 resolution touch screen. Light pen and touch screens tested with and without footswitch to enter data, all other devices used footswitch; touch screen tested on adjacent identical monitor as well as target monitor; velocity and scale factors subjectively optimized for all devices
- Experimental setup converted to mirror-image for left-handed subjects
- Questionnaire with seven-point Lickert scale to rate devices for comfort, ease of learning, and fatigue

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: type of control device, entry method, touch screen location
- Dependent variables: positioning speed (defined as a function of time between consecutive entries and the distance between targets, expressed in pixels/sec); positioning accuracy (defined as the number of pixels from the entered position to the center of target); subjective rating of devices
- Subject's task: position cursor to center of target
- 5 male and 3 female subjects, 2 left and 6 right-handed, with normal vision

Experimental Results

- Both lightpen and touch screen are significantly faster without the footswitch ($p < 0.01$). Positioning speed is significantly faster when the touch screen is on the display, rather than on an adjacent monitor ($p < 0.01$).
- Both lightpen and touch screen are significantly more accurate when used with the footswitch than without it ($0.01 < p < 0.05$). No significant difference in accuracy is found when the touch screen is on the display or on an adjacent monitor.
- Neither the footswitch nor the screen location has a significant effect on subjective ratings of comfort, or ease of learning for either lightpen or touch screen.
- The footswitch contributes to subjective fatigue with the lightpen, however.

Variability

Confidence intervals in figures indicate variability.

Repeatability/Comparison with Other Studies

Previous research has focused on only two or three devices at a time, making comparisons difficult, but, in general, results seem to be in agreement with these.

Constraints

- The results pertain only to the positioning tasks examined.

Key References

*1. Albert, A. E. (1982). The effect of graphic input devices on performance in a cursor positioning task. *Proceedings of the 26th Annual Meeting of the Human Factors Society* (pp. 54-58). Seattle, WA: The Human Factors Society.

2. Card, S. K., English, W. K., & Burr, B. J. (1978). Evaluation of mouse, rate-controlled isometric joystick, step keys and text keys for text selection on a CRT. *Ergonomics, 21*, 601-613.

3. English, W. K., Englebart, D. C., & Berman, M. L. (1967). Display-selection techniques for text manipulation. *IEEE Transactions on Human Factors in Electronics, HFE-8*, 515.

Cross References

12.421 Joystick type: effect on tracking performance

12.423 CRT Touch Screen Devices

Key Terms

CRT display; touch screen

General Description

Touch screen devices (TSDs) consist of a number of different technologies that can be overlaid on a CRT to allow subjects to make selections by touching predesignated areas of the screen (or its periphery). In general, all TSDs operate by producing x and y position data whenever a touch is detected by the system. The major use of TSDs is in combination with menu-selection dialogues. Certain advantages and disadvantages are commonly associated with touch screen techniques. Table 1 lists those that apply across the different design approaches. Important TSD design considerations are listed in Table 2. Important factors influencing user acceptance of TSDs are summarized in Table 3.

Constraints

- Specific TSD techniques may suffer from additional problems not listed in this general summary.

Key References

*1. Pfauth, M., & Priest, J. (1981). Person-computer interface using touch screen devices. *Proceedings of the 25th Annual Meeting of the Human Factors Society* (pp. 500- 504). Rochester, NY: The Human Factors Society.

Cross References

12.101 Recommended uses of controls;

12.102 Comparison of common controls;

12.301 Principles of grouping and arranging controls;

12.412 Control type, location, and turbulence: effect on data entry performance

Table 1. Advantages and disadvantages of touch screen devices. (From Ref. 1)

Advantages

- Direct visual-to-tactile control (input/output to one location)
- Fast data entry and control for certain tasks
- Minimal training (software flexible for different jobs and operator skill levels)
- Only valid options are available
- High operator acceptance
- Immediate feedback
- Symbolic graphic representation
- Minimal operator memorization required
- Minimal eye-hand coordination problems

Disadvantages

- Potentially high initial cost
- Increased programmer time
- Not as flexible for some types of input (unless used in combination with keyboard)
- Parallax affecting touch locations
- Screen glare
- Physical fatigue from reaching to screen
- Finger visually blocking the screen
- New method of programming interface software

Table 2. Design considerations for touch screen devices. (From Ref. 1)

Display Design Considerations

- Dialogue development/menu-hierarchy
- Selection feedback: auditory, tactile, or visual-inverting video seems preferred for TSDs
- Size of touch target: initial recommendation of 22 mm minimum diameter
- Shape and color coding of targets
- Distance between targets: dependent upon application but possible to program "dead zones" around target
- Activation force: nothing pertaining to TSDs
- Time delay between touches: programmable in some devices
- Mode: mixing performance considerations
- Resolution required for task
- Potential parallax problems
- CRT size to be used

Work Place Considerations

- Temperature and humidity extremes
- Electronic field interference
- Dirt, grease, and potential for damage to TSD surface
- Reach distance and fatigue

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 3. Factors in the acceptance of touch screen devices. (From Ref. 1)

Potential Users
• Those in extremely high-stress environments • Completely naive users • Users who have a predetermined limited interface with the computer system (e.g., management personnel) • Where available workspace does not allow a separate keyboard
Advantages
• No prior training needed; no need to learn how to use a keyboard or memorize commands • Dialogue technique can guide system user toward the desired information • The user is likely to view the system as a partner in the problem-solving process • User does not need to understand the specifics of how the system works • Limited error possibilities
Disadvantages
• Data entry through the TSD will be considerably slower than through the traditional keyboard • High cost to implement • Flexibility of system is dependent upon software capability, i.e., limited number of display options

12.424 Control Coding

Key Terms

Color coding; control coding; shape coding; size coding

General Description

Controls are coded to make them more easily identified and to ensure that they are operated correctly. The major coding methods discussed here include shape, texture, size, and color. Each method has its own advantage and disadvantage as shown in Table 1.

Shape (and texture)

The primary use of shape coding is in applications where illumination is low or where controls must be identified by touch without visual reference. However, shape coding has a visual component and can be used to supplement visual identification where appropriate. The maximum number of coding levels which should be used in a given application is between eight and ten when only touch discrimination is possible.

Size

Size coding has a visual as well as a tactual component, but is primarily used where low ambient illumination or task demands preclude visual identification. No more than five levels can be discriminated on a relative basis and no more than two or three on an absolute basis.

Color

Color can provide an effective means of coding when visual discrimination is possible. Since it is totally reliant on the visual modality, suboptimum viewing conditions can drastically affect its discriminability, so it is rarely used alone. The maximum number of controls that can be discriminated on an absolute basis is eight to ten. However, for most applications the number should not exceed five.

Applications

These coding methods can be used in combination to redundantly code information or to increase the number of available coding levels. Several factors should be taken into consideration when determining the appropriate code for a given application:

- Demands that will be placed upon the operator at the time controls are to be identified
- Illumination level of the operational environment
- Speed and accuracy with which controls must be identified
- Number of controls that must be coded
- Extent and type of coding already employed
- Space available for the location of controls.

Regardless of the method or combination of methods ultimately selected for a given application, it is very important that the technique be standardized and consistently applied throughout the system or equipment under design. Standardization reduces the training burden on the operator because of the positive transfer of learning from situation to situation. Failure to standardize, and the resultant negative transfer of learning, can reduce efficiency and may contribute to equipment damage or personal injury.

Key References

1. Gruber, A., & Bishop, E. W. (1962, January). *Guide to the coding of controls.* (Final Report). Fort Monmouth, NJ: U.S. Army Signal Research and Development Laboratory.

2. Hunt, D. P. (1953, August). *The coding of aircraft controls* (WADC-TR 53-221). Wright-Patterson Air Force Base, OH: Aero Medical Laboratory. (DTIC No. AD020796)

*3. U.S.Army Missile Command. (1981). *Human engineering design criteria for military systems, equipment and facilities* (MIL-STD-1472C). Philadelphia: Naval Publications and Forms Center.

Cross References

12.417 Continuous rotary controls: size coding;

12.418 Rotary selector controls: shape coding;

12.425 Push-button controls: shape coding;

12.430 Use of gloves: effect on discrimination of knob rim surface texture

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Table 1. Advantages and disadvantages of various types of coding. (From Ref. 3)

	Type of Coding		
	Shape	**Size**	**Color**
Advantages			
Improves visual identification	X	X	X
Improves nonvisual identification (tactual and kinesthetic)	X	X	
High discriminability between levels			X
Aids identification under low levels of illuminated and colored lighting	X	X	(when trans-illuminated)
May aid in identifying control position (setting)	X		
Disadvantages			
May require extra space	X	X	
Affects manipulation of the control (ease of use)	X	X	
Possibility of inadvertent control activation during discrimination	X	X	
May be less effective if operator wears gloves	X	X	
Discrimination affected by color and level of illumination			X
Long discrimination time	X	X	

12.425 Pushbutton Controls: Shape Coding

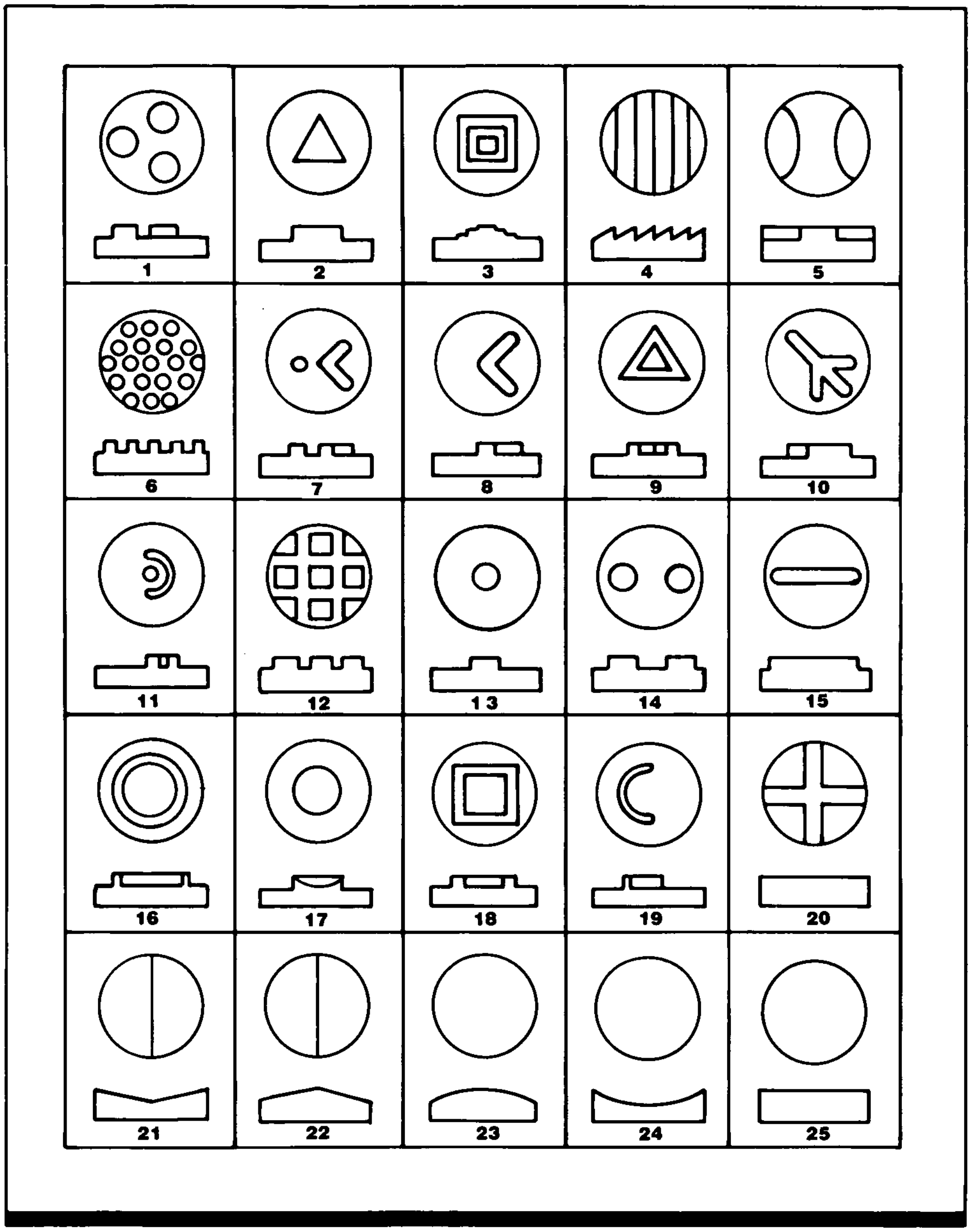


Figure 1. Shapes (front and side views) tested for tactile discrimination. (From Ref. 1)

Key Terms

Blind positioning; information portrayal; pushbuttons; shape coding; tactual pattern discrimination

General Description

The tops of pushbutton controls can be shape-coded so that a fingertip touch can discriminate among them. Figure 1 illustrates 25 possible shapes that can be used and Fig. 2 indicates the relative confusability among them. It can be seen that some clusters fall out, so that a coding set could be developed for a specific application with high discriminability.

Methods

Test Conditions

- Curtained aperture blocked subject's view
- Numbered matrix of shapes (Fig. 1) presented visually for shape comparison and identification
- 25 gray plastic control tops, each 2 cm diameter, 2 mm deep

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variable: shape of button top
- Dependent variable: shape confusability (defined as the frequency with which one shape is confused with another)
- Subject's task: reach through curtained aperture, touch shape with tip of forefinger, look at numbered matrix, identify shape being touched, state appropriate number from matrix
- Subjects instructed not to move or roll finger over shape

Experimental Results

- No shape is completely free from confusability.
- Figure 2 illustrates the relative confusability among the shapes.
- Shapes 1, 4, 21, 22, 23, and 24 in Fig. 1 are the most discriminable by touch alone.

Variability

No information on variability was given.

Constraints

- Details of methodology and statistical analyses (i.e., significance levels) are lacking.
- Subjects were ungloved; where flight gloves must be worn, discriminability would likely be reduced.
- No time constraints placed on subjects.

Key References

*1. Moore, T. G. (1974). Tactile and kinesthetic aspects of pushbuttons. *Applied Ergonomics, 52,* 66-71.

Cross References

9.208 Blind positioning accuracy: effect of target location;

9.209 Restricted blind-positioning: effects of distance and direction;

12.418 Rotary selector controls: shape coding;

12.424 Control coding

Response (columns); Stimulus (rows)

Stimulus	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	No Response
1	65					1						7	1	6												
2		71			3			1			1		3		1											
3		2	47		2		3			3	5		8			1	1			1						7
4				71		3						6														
5		10			57				1			1			3					7					1	
6	1			1		45		1		1	1	30														
7	2	1	2				58	4	2	7	1			1					1	1						
8		1	1					60							2	1			15							
9		1			1		2	2	63		1	1						8	1							
10						3	16		1	39	10	2				1		4		4						
11	1	2	4			4	14			4	37		1	7				1								5
12	1			8		22	1				1	47														
13		4	2				1						72	1												
14	7					1	1							71												
15		2			4			3		1					69					1						
16									2		1					50	9	10	1					1	6	
17		1				1			2	1						4	65	2						1	3	
18										12						7		60	1							
19								4	21									1	54							
20			1		4		1		2	3	1				1					67						
21															1						79					
22			1		1										1							75	1		1	
23																						1	79			
24																		1			3			75	1	
25					1															/			5	1	73	

Figure 2. Frequency with which a pushbutton of given shape (stimulus) was identified as each of the possible shape variants (response). (From Ref. 1)

12.426 Use of Gloves: Effect on Control Operation

Key Terms

Gloved operations; keyboards; rotary selector switches; thumbwheel switches; toggle switches

General Description

The effect of wearing gloves on control operations is not well researched. In the past 25 years, only a few studies have found their way into the literature. It is apparent from examining these studies that the impact of wearing gloves depends very much on the type of control, the nature of the task, and the characteristics of the gloves. Further, it should be noted that the effect of a cold environment on the bare hand may be as degrading to performance as are gloves.

Five areas are examined in related entries in which gloves might be expected to influence control operations:

- Control operation time
- Maximum rotary torque applied to rotary controls
- Keyboard data entry
- Thumbwheel data entry
- Control rim surface discriminability.

While no consistent pattern of influence is apparent from the studies, some general statements about the characteristics of gloves and control actions can be offered.

Control operating time is generally increased when gloves are worn, particularly when control surfaces are smooth and gloves are either thick or loose fitting. An exception occurs when gloves serve to protect the hand (e.g., toggle switch activation), and operation time may be decreased if the glove is well fitting and pliable.

The maximum torque that can be exerted on rotary controls is reduced when gloves are worn, but the effect is small and may have no operation impact.

Keyboard data entry is not generally affected by wearing light gloves unless very rapid entry is required and the glove surface slips easily on the keys.

Data entry performance with thumbwheels is not affected by the wearing of gloves. This is not surprising, since very little manual flexibility is required for such tasks. Wearing gloves generally reduces the discriminability of control shapes. This effect, however, will vary, depending on the tactual sensitivity required for the discrimination, and the thickness of the glove.

The influence of wearing gloves on control manipulation is a complex issue. The effect varies as a function of the physical characteristics of the control type, the nature of the control operation, and the characteristics of the gloves worn. Some controls for which data are missing include: rocker switches, joysticks, trackballs, mouses, slide switches, rotary selectors, push-pull switches, and touch screens.

Key References

1. Taylor, R. M., & Berman, J. V. F. (1982). Human factors in aircraft keyboard design: Standards, issues, and further evidence relating to gloves and key characteristics. *Advisory Group for Aerospace Research & Development conference proceedings* (AGARD-CP-329). London: Technical Editing and Research Ltd.

Cross References

12.427 Use of gloves: effect on control operating time;

12.428 Use of gloves: effect on maximum torque applied to rotary switches;

12.429 Use of gloves: effect on keyboard data entry;

12.430 Use of gloves: effect on discrimination of knob rim surface texture

Notes

12.427 Use of Gloves: Effect on Control Operating Time

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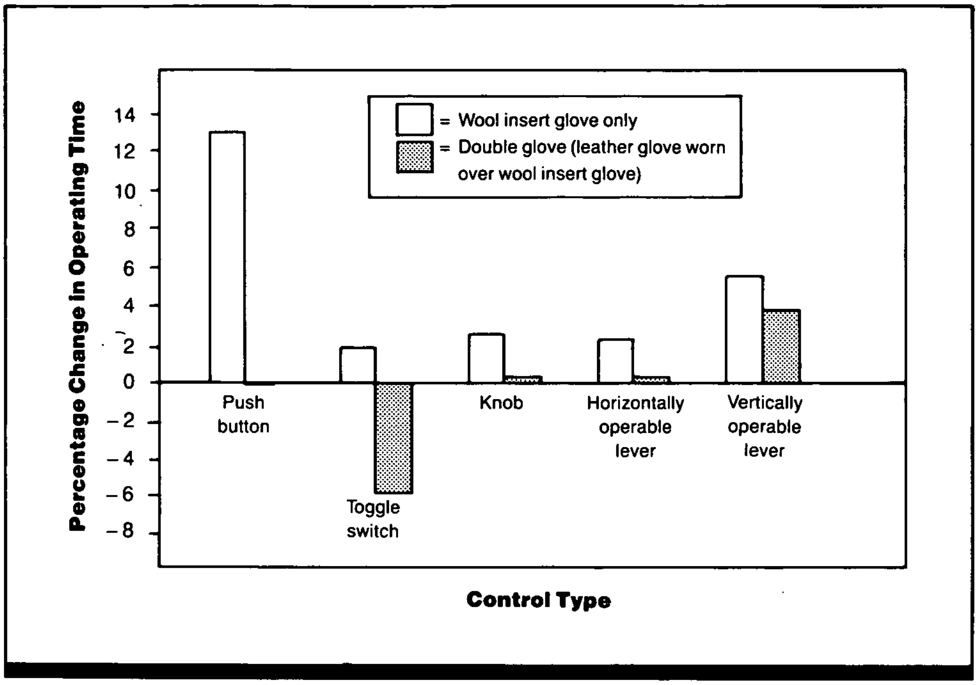

Figure 1. Percentage of operating time increase (or decrease) as a function of wearing gloves for various control types. (From Ref. 1)

Key Terms

Gloved operations; horizontal levers; manual controls; pushbuttons; reaction time; rotary selector switches; toggle switches

General Description

The effect of wearing gloves upon control operation time varies with the type of gloves worn, the physical characteristics of the control, and the type of operation required. At temperatures comfortable to the bare hand, gloves may either increase or decrease control operation time. The use of a well-fitting, pliable, heavy, protective glove with a non-slip outer surface may decrease operating times when rapid control operation might injure the unprotected hand (e.g., toggle switch activation). A loosely fitting glove of non-protective material that slips easily on the control surface may increase operation times without decreasing the subject's ability to make sensitive or quick adjustments for all types of controls, especially those that have smooth surfaces and cannot be tightly gripped or squarely hit (e.g., on-off controls).

Methods

Test Conditions

- One of each of five types of controls (toggle switch, rotary knob, pushbutton, and vertical and horizontal levers) arranged on panel 25.4 cm high and 30.5 cm wide; four panels arranged horizontally at about shoulder height, two panels to left and two to right of shoulder line
- Signal light next to each discrete control illuminated to signal trial onset and control to be operated; one of two illuminated as continuous controls to show direction in which to move control as well as to signal trial onset; light extinguished when correct control position achieved
- After each control operation, subject's four fingers of right (operating) hand on key placed horizontally on top of one panel and slightly to right of right shoulder line
- Hand bare, or covered with wool insert glove or leather glove over wool insert glove

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: type of control, type of hand covering
- Dependent variable: control operation time (defined as time from illumination of signal light until control correctly operated)
- Subject's task: use right hand to operate control to extinguish signal light
- 30 right-handed male college students

Experimental Results

- Operation time for the pushbutton is significantly longer ($p < 0.001$) when the wool insert glove is worn than when either the bare hand or double glove is used.
- Operation time for the toggle switch is significantly shorter ($p < 0.05$) when the double glove is worn than when either the bare hand or the wool insert glove is used.
- Operation time for the vertically operated lever is signifi-

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

cantly longer ($p < 0.05$) with the wool insert glove and is longer than with the bare hand, but not significantly so.
- Operating times are longer for all control types with the wool insert glove than with the bare hand for 95% of control operations.
- Operating times are longer for all control types with the wool insert glove than with the double glove for 85% of control operations.
- Operating times vary among control types; toggle switch and pushbutton operating times are shortest.

Variability

No formal reliability analyses reported. Graphic analysis indicated no consistent within-sample differences between double glove and barehanded operation of the pushbutton, rotary knob, and horizontal lever, but differences existed for the toggle switch and possibly for the vertical lever.

Repeatability/Comparison with Other Studies

Differences in design and procedures make comparisons among studies difficult or impossible.

Constraints

- Control operating times vary in part due to distance from hand key used as the starting point for each trial. Generalization of control operating times to other applications must take into account differences in control locations from those studied here.
- Data were collected in a 20°C environment. Times for bare-handed control operation may not be valid with colder ambient temperatures.
- Controls used in this study were relatively large and well spaced. Increased operating times may result from gloved operation when controls are small or crowded and highly accurate finger-aiming is required.

Key References

*1. Bradley, J. V. (1969) Effect of gloves on control operation time. *Human Factors, 11*, 13-20.

Cross References

12.426 Use of gloves: effect on control operation;

12.428 Use of gloves: effect on maximum torque applied to rotary switches;

12.429 Use of gloves: effect on keyboard data entry;

12.430 Use of gloves: effect on discrimination of knob rim surface texture

Table 1. Mean control operating times in seconds. (Adapted from Ref. 1)

	Bare Hand	Wool Insert	Double Glove	Mean Across Conditions
Toggle Switch	0.50	0.51	0.47	0.49
Rotary Knob	1.24	1.28	1.25	1.26
Pushbutton	0.58	0.65	0.58	0.60
Horizontal Lever	1.15	1.18	1.16	1.16
Vertical Lever	1.22	1.29	1.27	1.26

12.428 Use of Gloves: Effect on Maximum Torque Applied to Rotary Switches

Key Terms

Gloved operations; rotary selector switches

General Description

Gloves have a significant but small effect on the maximum torque which can be applied to rotary controls. Both control orientation and knob diameter also have a significant effect on performance. While all three of these main effects (and some interactions) are significant, only knob diameter has a great enough effect to be of practical importance in an applied setting. In general, the maximum torque increases as the knob diameter is increased from 0.95-1.91 cm.

Methods

Test Conditions

- Test apparatus: dial indicating, screwdriver-type torque wrench, with both maximum reading resettable indicator and regular pointer; mounted on rigid base and located behind control panel 15.24 cm high and 10.16 cm wide; placed 30.48 cm from edge and on top of 73.66-cm high table
- Control knobs: solid aluminum, diamond knurled, 1.27 cm long with diameters of 0.95, 1.27, and 1.91 cm; mounted on torque wrench shaft, flush with and in center of control panel
- Orientation: facing or to right of subjects, changed by ratio apparatus 90 deg
- Hand condition: gloved or ungloved; standard Air Force double gloves
- Groups: civilian and military
- 12 trials per condition

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: orientation, control knob diameter, hand condition, military or civilian status
- Dependent variable: maximum torque exerted
- Subject's task: turn control knob with preferred hand while holding apparatus with other hand
- Subjects instructed to twist as hard as possible; provided no feedback on performance during testing; subjects standing
- 120 male subjects, 96 civilian engineers and technicians, 24 military technicians, all under 40; 7 subjects left-handed

Experimental Results

- Maximum torque is significantly influenced ($p < 0.01$) by size of knob, hand condition, and control orientation. In general, torque increases with increasing knob size and with side knob orientation, and decreases when wearing gloves.
- There are significant ($p < 0.01$) interactions between knob diameter and hand condition, and between groups, gloves, and orientation. In general, the differences between gloves and bare hands are less marked for the 1.27-cm diameter knobs, and gloves hinder civilians less in the side knob orientation.
- Only knob size has a substantial impact on performance.

Variability

Within-subject variability not reported; between-subject reliability appears high (See Table 1).

Repeatability/Comparison with Other Studies

No similar studies located.

Constraints

- All operations were from the standing position, with the knob at near-optimum location and in close proximity to the subject. Where conditions are less optimal, the maximum exertable torque would likely be lower than indicated in Table 1.
- Other conditions, such as moisture, icing, dirt, and operator fatigue may also reduce the maximum exertable torque which can be produced.

Key References

*1. Swain, A. D., Shelton, G. C., & Rigby, L. V. (1970). Maximum torque for small knobs operated with and without gloves. *Ergonomics, 13*, 201-208.

Cross References

7.113 Probability of correctly operating continuous controls while monitoring dynamic displays;

12.413 Rotary selector switches;

12.418 Rotary selector controls: shape coding;

12.426 Use of gloves: effect on control operation;

12.427 Use of gloves: effect on control operating time;

12.429 Use of gloves: effect on keyboard data entry;

12.430 Use of gloves: effect on discrimination of knob rim surface texture

Table 1. Maximum exertable torque (mN-M). (From Ref. 1)

	0.953-cm Knob				1.27-cm Knob				1.91-cm Knob			
	Gloved		Bare		Gloved		Bare		Gloved		Bare	
Mean Torque	**Front**	**Side**	**Front**	**Side**	**Front**	**Side**	**Front**	**Side**	**Front**	**Side**	**Front**	**Side**
Military Subjects	454.9	469.6	482.2	543.5	576.7	595.2	601.1	631.2	938.3	912.7	1042.8	1094.8
Civilian Subjects	449.9	470.2	534.9	550.3	570.4	594.9	661.0	667.4	915.5	935.5	1126.8	1147.4
Overall	450.9	470.1	524.4	548.9	571.6	594.9	649.1	660.1	920.0	930.9	1110.0	1136.8
Overall Standard Deviation (SD)	84.3	97.6	127.3	124.7	104.0	116.1	150.1	159.0	170.25	178.0	260.5	265.9
SD Divided by Mean	0.19	0.21	0.24	0.23	0.18	0.20	0.23	0.24	0.18	0.19	0.23	0.23
5th Percentile (Mean – 1.65 SD)	311.8	309.1	313.2	343.2	400.0	403.4	401.6	397.7	639.1	637.3	680.2	698.2

12.429 Use of Gloves: Effect on Keyboard Data Entry

Key Terms

Gloved operations; key resistance; keyboards

General Description

In general, where data entry is relatively slow and discontinuous, aircrew gloves are likely to have little effect on speed or accuracy of data entry performance. Auditory feedback is not found to aid keying performance under these conditions. Reducing key travel appears to improve keying speed, and increasing key resistance appears to improve keying accuracy. Where both speed and accuracy are important, low-key travel and high-key resistance may be the best combination.

Methods

Test Conditions

Experiment 1

- Bare hands, cape leather glove, winter glove, liner, cape leather glove and liner, winter glove and liner
- Telephone keyset layout, "ENTER" and "ERROR" keys below and on either side of zero
- Key size 19 × 13 mm, 13-mm separation, 3-mm travel, 2.5 N resistance
- Seven-digit number and white noise presented binaurally through headphones
- First-order joystick, vertically moved cursor on monitor in head-up display location

Experiment 2

- Cape leather glove or bare hand
- Three keys in row, key parameters as in Exp. 1, LED above each key, when on (randomly lit), indicated next correct key press, correct key press shortened and incorrect press lengthened next correct key availability
- White noise, with or without auditory feedback (20 msec at 1 kHz), presented binaurally through headphones

Experiment 3

- Same hand conditions as in Exp. 2
- Three keys used as in Exp. 2, key size 15 × 15 mm, 13 mm separation; key travel-force conditions: 2 mm-1 N, 10 mm-1 N, 2 mm-15 N, 10 mm-15 N; one or three finger data entry

Experimental Procedure

- Repeated measures design, counterbalanced for order effects
- Independent variables: Exp. 1: hand condition; Exp. 2: hand condition, auditory feedback; Exp. 3: hand condition, key travel, key force, number of fingers used
- Dependent variables: data entry time, error rate, error type, tracking error (Exp. 1 only)
- Subject's task: Exp. 1: input data with left hand while tracking cursor with right; Exps. 2 and 3: press keys to extinguish lit LED using preferred hand
- Between 6 and 16 subjects per experiment; inexperienced males

Experimental Results

- Experiment 1: no significant differences in response time, error rate, or error type are found for telephone keyset data entry as a function of wearing gloves. However, there is a significant increase ($p < 0.05$) in tracking errors when gloves are worn.
- Experiment 2: no significant effects on the number or type of data entry errors are found as a function of wearing gloves. However, correct response time is significantly increased ($p < 0.01$) when gloves are worn. Performance is unaffected by auditory feedback.
- Experiment 3: no significant differences in response time, error rate, or error type are found as a function of wearing gloves. However, there are significant main effects and interactions for force, travel, and finger conditions: (1) response time increases as key travel is increased ($p < 0.01$), (2) long response times are associated with the 10 mm-15 N travel-force condition ($p < 0.05$), (3) three-finger data entry is significantly slower ($p < 0.05$) than one-finger entry, (4) long response times are associated with three-finger keying at maximum force, (5) long response times are associated with three-finger keying on the high-force condition, (6) the number of keying errors is significantly reduced in the low-force condition ($p < 0.001$) and the low-travel condition ($p < 0.05$), (7) an increase in errors is associated with the low-force condition ($p < 0.001$).

Variability

No information on variability was given.

Repeatability/Comparison with Other Studies

The insignificant effect of auditory feedback is supported by other studies (Ref. 3). The significant effect of key travel and displacement is at odds with the literature. Other researchers (Ref. 1) have found that these variables have little effect on the performance of experienced typists. This difference may be due to the relatively slow typing speeds attained here. The general lack of performance decrement with gloves is supported by Meredith (Ref. 4), who found that manual dexterity with cape leather gloves is almost as good as with bare hands. Further support is lent by Bradley (Ref. 2), who reports no differences in pushbutton operating speed when gloves are worn.

Constraints

- The lack of consistent performance decrements with gloves may be due to the relatively low keying rates achieved. Tasks involving more rapid and continuous data entry (such as by skilled typists) are more likely to be affected by the wearing of gloves.

Key References

1. Alden, D. G., Daniels, R. W., & Kanarick, A. F. (1972). Keyboard design and operation: A review of the major issues. *Human Factors, 14*, 275-293.

2. Bradley, J. V. (1969). Effects of gloves on control operating time. *Human Factors, 11*, 13-20.

3. Deininger, R. L. (1960). Human factors engineering studies and use of pushbutton telephone sets. *The Bell System Technical Journal, 39*, 995-1012.

4. Meredith, A. E. (1978). *Manual dexterity tests and real military tasks: A validation study comparing bare hands, NBC gloves, pilot gloves and Arctic gloves.* (APRE Report #20/77). Farnborough, Hants: Army Personnel Research Establishment.

*5. Taylor, R. M., & Berman, J. V. F. (1982). Ergonomic aspects of aircraft keyboard design: The effects of gloves and sensory feedback on keying performance. *Ergonomics, 25*, 1109-1123.

Cross References

12.407 Conventional versus membrane keyboards;

12.408 Alphabetic versus QWERTY keyboard arrangements;

12.409 Keyboard slope: effect on keying performance;

12.426 Use of gloves: effect on control operation;

12.427 Use of gloves: effect on control operating time;

12.428 Use of gloves: effect on maximum torque applied to rotary switches;

12.430 Use of gloves: effect on discrimination of knob rim surface texture

12.430 Use of Gloves: Effect on Discrimination of Knob Rim Surface Texture

Table 1. Frequency of incorrect responses with bare hands (Exp. 1, 5.08-cm knobs). (From Ref. 1)

Wrong Response	Knob: *A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	
A	X										Smooth
B		X	6								Fluted (6 troughs)
C		3	X	1							Fluted (9 troughs)
D			6	X							Fluted (18 troughs)
E					X	11	1	4	1		Rectangular knurl (full)
F					8	X	7	8	5	6	Rectangular knurl (half)
G					1	7	X		15	9	Rectangular knurl (quarter)
H					6	7		X	1	2	Diamond knurl (full)
I					1	7	6	5	X	18*	Diamond knurl (half)
J						5	4	1	21*	X	Diamond knurl (quarter)

* Does *not* differ significantly, at the one-tailed .05 level, from frequency expected by chance.
Maximum possible cell entry = 45.

Key Terms

Fluted knobs; gloved operations; knurled knobs; rotary selector switches; shape coding; smooth knobs

General Description

Wearing gloves reduces the discriminability of control shapes and textures. However, this effect varies with the type of shape coding employed. A smooth knob is still easily discriminated from either fluted or knurled knobs when gloves are worn. The discriminability of fluted knobs, both within their own class and when compared to other classes, is only slightly affected by the wearing of gloves. The discriminability of knurled knobs (both rectangular and diamond types) is greatly reduced by the wearing of gloves.

Methods

Test Conditions

- Subjects seated facing apparatus window with full-sized photos of two alphabetically labeled knobs and curtained aperture through which subjects reached to feel knob
- Experiment 1: ten 1.27 cm thick, 5.08 cm diameter, cylindrical, aluminum knobs; *A* = smooth rim, *B* = fluted: six troughs (humps and troughs subtending equal chords 1.27 cm long, trough depth 0.318 cm), *C* = fluted: nine troughs (humps and troughs subtending equal chords 0.873 cm long, trough depth 0.218 cm), *D* = fluted: 18 troughs (humps and troughs subtending equal chords 0.437 cm long, trough depth. 099 cm), *E* = full rectangular knurl, *F* = half rectangular knurl, *G* = quarter rectangular knurl, *H* = full diamond knurl, *I* = half diamond knurl, *J* = quarter diamond knurl
- Experiment 2: seven 1.27 cm thick, 2.54 cm diameter, cylindrical, aluminum knobs, *a* = smooth rim, *b* = fluted: six troughs (humps and troughs subtending equal chords 0.635 cm long, trough depth 0.159 cm, *c* = fluted: nine troughs (humps and troughs 0.437 cm long, trough depth 0.119 cm), *d* = fluted: 18 troughs (humps and troughs subtending equal chords 0.218 cm, trough depth 0.060 cm), *f* = half rectangular knurl, *h* = full diamond knurl, *j* = quarter diamond knurl
- Double flying glove (MA-1): wool insert and leather outer shell

Experimental Procedure

- Repeated measures design, counterbalanced for knob presentation order
- Independent variables: knob rim surface, hand covering condition (gloves or bare hands)
- Dependent variable: the number of times a knob was incorrectly identified
- Subject's task: reach through curtained aperture, feel knob, call out letter designation (from two photos)
- No time constraint on subjects; gloved discriminations followed bare hand discriminations
- 45 right-handed college students in Exp. 1; 21 right-handed male college students in Exp. 2

Experimental Results

- In terms of general discriminability, the smooth knob is the best, followed by the fluted, rectangular knurled, and diamond knurled knob classes. Fluted knobs tend to be confused only with other fluted knobs. Rectangular and diamond knurled knobs tend to be easily confused within and between their classes.
- Experiment 2 (Tables 4 and 5), which used smaller knobs, generally replicates the findings of Exp. 1 (Tables 1 and 2), with the exception that fluted class knobs tend to be confused with the knurled class due to their small trough size.
- Wearing gloves tends to generally reduce the discriminability of knobs (see Table 3). Smooth knob identification is virtually unaffected by the wearing of gloves, while fluted class identification is only slightly affected. However, the discriminability of the knurled classes of knobs is greatly reduced when gloves are worn.

Variability

No information on variability was given.

Table 2. Frequency of incorrect responses with gloved hands (Exp. 1, 5.08-cm knobs). (From Ref. 1)

Wrong Response	Knob *A*	*B*	*C*	*D*	*E*	*F*	*G*	*H*	*I*	*J*	
A	X										Smooth
B		X	1								Fluted (6 troughs)
C		11	X								Fluted (9 troughs)
D		2	7	X							Fluted (18 troughs)
E				1	X	10	8	18*	5	3	Rectangular knurl (full)
F					14	X	17*	19*	8	13	Rectangular knurl (half)
G					5	15	X	16	25*	22*	Rectangular knurl (quarter)
H					16	14	8	X	2	8	Diamond knurl (full)
I					13	12	12	17*	X	20*	Diamond knurl (half)
J						8	13	11	26*	X	Diamond knurl (quarter)

* Does *not* differ significantly, at the one-tailed .05 level, from frequency expected by chance.
Maximum possible cell entry = 45.

Table 3. Percentage of misidentification trials in Exp. 1 as a function of type of rim surface and hand condition. (From Ref. 1)

Hand Condition	Rim Surface of Alternative Knob	Rim Surface of Knob: Smooth	Fluted	Rectangular Knurl	Diamond Knurl
Bare	Smooth	X	0	0	0
	Fluted	0	5.93	0	0
	Rectangular Knurl	0	0	12.96	11.85
	Diamond Knurl	0	0	8.89	17.78
	Any of Above	0	1.32	5.84	7.90
Gloved	Smooth	X	0	0	0
	Fluted	0	7.78	0	0
	Rectangular Knurl	0	.25	25.56	31.85
	Diamond Knurl	0	0	23.70	31.11
	Any of Above	0	1.81	13.58	17.53

Constraints

- Due to the somewhat artificial nature of the tasks (i.e, a dichotomous choice), the discriminability shown here is probably higher than would be seen in a real-life multi-knob application.
- Since all glove discriminations were made after all bare-handed discriminations, the detrimental effect of wearing gloves may have been muted.

Key References

*1. Bradley, J. V. (1967). Tactual coding of cylindrical knobs. *Human Factors*, 9, 483-496.

Cross References

12.417 Continuous rotary controls: size coding;

12.418 Rotary selector controls: shape coding;

12.426 Use of gloves: effect on control operation;

12.427 Use of gloves: effect on control operating time;

12.428 Use of gloves: effect on maximum torque applied to rotary switches;

12.429 Use of gloves: effect on keyboard data entry

Table 4. Frequency of incorrect responses with bare hands (Exp. 2, 2.54-cm knobs). (From Ref. 1)

Wrong Response	Knob: *a*	*b*	*c*	*d*	*f*	*h*	*j*	
a	X							Smooth
b		X	4	1				Fluted (6 troughs)
c		8*	X					Fluted (9 troughs)
d		2	15*	X		1		Fluted (18 troughs)
f				3	X	5		Rectangular knurl (half)
h					5	X		Diamond knurl (full)
j					1		X	Diamond knurl (quarter)

*Does *not* differ significantly, at one-tailed .05 level, from frequency expected by chance.
Maximum possible cell entry = 21.

Table 5. Frequency of incorrect responses with gloved hands (Exp. 2, 2.54-cm knobs). (From Ref. 1)

Wrong Response	Knob: *a*	*b*	*c*	*d*	*f*	*h*	*j*	
a	X							Smooth
b		X	2			1		Fluted (6 troughs)
c	1	8*	X					Fluted (9 troughs)
d		2	6	X		2		Fluted (18 troughs)
f				8*	X	8*	2	Diamond knurl (half)
h				9*	5	X	3	Diamond knurl (full)
j			1	5	5	9*	X	Diamond knurl (quarter)

*Does *not* differ significantly, at one-tailed .05 level, from frequency expected by chance.
Maximum possible cell entry = 21.

Boff, K. R., & Lincoln, J. E. *Engineering Data Compendium: Human Perception and Performance.* AAMRL, Wright-Patterson AFB, OH, 1988.

Key Terms