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AN APPROACH TOWARD FUNCTION ALLOCATION BETWEEN HUMANS AND MACHINES IN SPACE STATION ACTIVITIES

By Georg von Tiesenhausen
Program Development

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16. ABSTRACT

Present NASA and contractor studies are evolving toward the definition of a future manned permanent space station. This report attempts to provide certain basic guidelines and data to assist in the allocation of functions between humans and automated systems and for human/machine participation. The report describes the significant human capabilities and limitations and provides criteria and guidelines for various levels of automation and human participation. An appendix contains a collection of human factors data.

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PREFACE

This report is the result of the author's participation in the workshop on "The Human Role In Space." August 24 through 26, in Leesburg, Virginia. This workshop was sponsored by the Office of Aeronautics and Space Technology, NASA Headquarters, and managed by Dr. Melvin D. Montemerlo of that office.

The information gathered at that conference has been organized and adapted to the requirements of a space station, emphasizing the problem of task allocation between humans and machines.

It is hoped that the information presented here is of interest and may be helpful in stimulating specific investigations in this area.

ACKNOWLEDGMENTS

The author gratefully acknowledges the valuable comments from Mr. David B. S. Smith, Space Systems Laboratory, Massachusetts Institute of Technology, and the discussion with him of the various tables in this report.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF CHARTS IN APPENDIX

TECHNICAL MEMORANDUM

AN APPROACH TOWARD FUNCTION ALLOCATION BETWEEN HUMANS AND MACHINES IN SPACE STATION ACTIVITIES

1.0 INTRODUCTION

Present NASA and contractor studies are evolving toward the definition of a future manned permanent space station. During the early stages of design, informed decisions must be made about the allocation of functions between humans and automated systems and for the combination of both in order to maximize mission success, efficiency, safety, and economics.

In the past, decisions on task allocations have been made more often unconsciously and unrecorded, than consciously and explicitly. A continuation of the past lack of deliberation on this subject may be quite penalizing in the most complex human-machine relationship as presented by a manned permanent space station.

The complexity of planned space station missions may create workloads that at times impose intolerable demands on crews, therefore, development and application of automated features can improve the effectiveness of space station operations.

The technology for automation of all routine tasks and of some others is now available. Available modern microprocessor technology and display systems and the advent of expert systems and others make it entirely feasible to automate specific space station systems and functions which previously were considered to be operated manually.

The need to apply automation technology to advanced missions in general and to a space station in particular is described below:

Cost of Ground Support – Current ground operations are reliant on large teams of specialists to perform functions such as fault detection, fault isolation, failure mode workaround, command processing, and tracking processing. It is becoming less feasible to maintain these large cadres of technical people during flight operations due to economic limitations. Furthermore, these individuals in a typical operation scenario are under-utilized until a failure occurs. With the maturing of decision-aiding techniques such as expert systems, it is becoming feasible to supplement individuals with aids that more effectively extract information from the ever-increasing volume of data. This, in turn, will enable the large cadres of individuals to be significantly reduced while increasing the ability of operators to make decisions effectively.

Man Support in Hazardous Environments – The cost of supporting man in the hostile space environment is necessarily much larger than that of supporting an unmanned system. Manned vehicles must incorporate costly life support systems which decrease vehicle payload capacity. The quality of components and level of redundancy for manned vehicles must be higher than those for unmanned missions. However, human problem solving capabilities are still required for many applications. For some near-term applications, it will be feasible to automate the control process in order to remove man from the system. For more complex operations, problem solving abilities may be remotely incorporated through telepresence and remote man-in-the-loop control. As the state of the art in automated problem solving advances, the individual can be removed from the control loop and will become a supervisor over an automated system.

Non-Optimal Human Control – Laboratory studies have shown that if good models of the system dynamics and appropriate control laws can be developed and implemented in real time, an automated system provides more optimal control than does a man in the loop. This has been demonstrated during physical simulations for rendezvous and docking but applies as well to other areas such as manipulator control.

Psychological Considerations – When placed in a highly-repetitive, mundane environment, humans have a tendency to become lackadaisical and make mistakes. Many of the tasks inherent in space operations and ground support have this quality. Decision aids in this environment would reduce the repetition and provide a means to quickly evaluate the volumes of data, provide a synopsis of the data, generate recommendations, and allow the human to use the inherent powers of reasoning more effectively.

Limited Strength – For many application scenarios such as payload retrieval, limited human strength becomes a negative factor. Furthermore, human dexterity is significantly reduced by the cumbersome life support equipment required in space. With the state of the art in actuators and materials, it is possible to develop mechanisms that deliver more torque with faster response times than a human counterpart.

In developing future manned space stations, sufficient attention must be paid to past and present efforts in automation and the human role in comparable systems. This will help to repeat past successes and avoid past shortcomings.

There is currently no systematic, widely applied methodology available for allocating of functions between automated systems and astronauts. Similarly, there is no criterion for balancing the cost of automating particular functions against the resulting improvements in space station performance.

The current absence of a systematic approach to task allocations between humans and machines in space stations constitutes a serious void in developing space station systems and functions. This report intends to assist in arriving at an efficient space station design approach for maximum returns within limited resources by providing an approach to a rational guide to allocate tasks between astronauts and machines in the context of human capabilities and limitations until a more in-depth approach to this problem addressing specific systems, is available.

1.1 Definition of Automation

While the term "human factor" is rather explicit, the term "automation" is ambiguous and has diverse interpretations. It is used variously to describe the control of a single quantity by a very simple on-off mechanism (e.g., thermostat). It is used to describe the concurrent display of data from several sources to a person for interpretation (e.g., Shuttle crew station). Automation has also been used to describe the control of complex processes in which the automated system replaced some human intellectual capabilities (e.g., mission sequencing). Certain human decision processes can be done by machines and called automated.

In this report the term "automation" shall describe any effort to allocate physical and abstract tasks to machines with various levels of human participation. This broad definition appears appropriate for a manned space station with its wide scope of functions.

1.2 General Objectives of Space Station Automation

The proper application of space station automation shall include benefits in the following areas:

1) Performance of functions that humans are not capable of performing or because of cost, time, and safety constraints imposed by manual performance

2) Provide better solutions to a problem than humans

3) More cost-effective, reliable, or consistent

4) Decreased workload

5) Increased safety margin

6) Increased quality of life for astronauts

7) Ease of learning to operate a system

8) Speed and convenience in actual use

9) Increased operating efficiency

10) Increased schedule dependability.

2.0 SPACE STATION SYSTEMS AND FUNCTIONS

2.1 Classification of Systems and Functions

It is convenient to divide space station systems and functions into two classes each of which is different in its expected human role, type and character of activities, approach to human/machine task allocation, and development needs (Table 1). These classes are:

Class A:

- Includes all systems and functions that are necessary to sustain the basic space station in an operational mode (core systems)
- Human involvement should be minor because it is unproductive
- These operations are constant and essentially fixed, therefore a singular approach toward task allocation and integration of humans/systems is possible
- This class of operations must be part of the space station development.

Class B

- Includes all systems and functions that constitute the objectives of having a space station (performing experiments, application tasks, construction, satellite services, etc.)

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TABLE 1. CLASSIFICATION OF SPACE STATION SYSTEMS AND FUNCTIONS

	A	B
	Space Station Related Systems Operations and Maintenance	Experiments, Applications, Construction, S/C Servicing Etc.
	Unproductive Activities	Productive Activities
Expected Human Role	• Minor	• Major
Type and Character of Activities	• Essentially fixed ("core" systems)	• Continually changing
Approach to Human/Machine Task Allocations	• Singular	• Diverse, individual
Development Needs	• Integrated human/systems automation for "core" systems functions	• Integration between activities and with space station systems and functions (model)
Responsibility	• Space station development	• Individual project development

- Human involvement should be major because these activities constitute the reason for human presence and are, therefore, productive.
- These systems and functions change continually and, therefore, a model is required for human/machine task allocation and integration.
- This class of operations requires a two-stage integration: between different systems and functions and with the space station interfaces.
- This class of operations must be part of the individual project development.

2.2 Space Station Core Systems and Functions

Table 2 lists systems and activities that are expected to exist in all space stations and, therefore, can be co. ·'dered generic. It is understood that these generic systems are generally those that maintain the functions of the space station proper. In some cases they may also support Class B activities.

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TABLE 2. SPACE STATION CORE SYSTEMS AND ACTIVITIES

Class A (Core Areas)

- Environmental control and life support
- Communication
- Systems control and display
- Power source
- Power management and distribution
- Data information and management
- Propulsion
- Flight control (including formation flights, Shuttle interaction, altitude reboost, etc.)
- Malfunction warning and reconfiguration
- Thermal control
- Inventory control (expendables, equipment, etc.)
- Activity schedule control
- Software control
- External environmental control
- Configuration control (build-up phase, growth adjustment, etc.)
- Traffic control
- Manipulator control
- TMS (OTV) checkout and launch control
- Others

Those generic systems that may serve both Classes A and B are the Data and Information Management, Thermal Control, and Inventory Control Systems. The reason for this is the more up-to-date technology of the Class B systems versus the space station Class A systems which may have their technology frozen several years before the station's initial emplacement (e.g., the Space Shuttle on-board computers are about 1971/72 technology while experiment electronics may have more recent technology). Cost trade-offs will decide for these Class B functions if central or peripheral control has more advantages.

All core systems and functions can be divided into core performance areas (Table 3). These seven performance areas were compiled from a great deal of literature in the area of optimal human performance in systems [1]. These areas were defined as performance areas that could be used to describe any system and function.

Table 4 expands the classification of core performance capabilities with specific examples and related required resource characteristics. It should be noted that this classification often has considerable overlap between several areas but is maintained to provide a well manageable structure to be used for later task allocation efforts.

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TABLE 3. CORE PERFORMANCE AREAS [9]

1. Monitoring	5. Decision Making
2. Sensing	6. Information Storage
3. Information Processing	7. Controlling
4. Interpreting	

TABLE 4. CLASSIFICATION OF CORE PERFORMANCE CAPABILITIES [1]

Monitoring

To maintain a state of readiness or preparation for receipt of inputs

Examples	Requires Resource Characteristics
Search	High reliability in detecting signals
Surveillance	Monitoring specific physical energies
Vigilance	Monitoring of infrequent events
Watch-keeping	Monitoring scheduled or predictable events Continuous attention Monitoring of long-duration events

Sensing

To perceive external stimuli, to recognize a change of external state, to acquire data from the environment

Examples	Required Resource Characteristics
Perception	Sensing specific physical energies
Signal Detection	Sensing a stimulus against a background of noise
Signal Recognition	Sensing the same stimulus frequently
Discrimination	Sensing several similar stimuli simultaneously
Recognition of Discrete Change	Sensing quantitative values
Recognition of Dynamic Change	Simultaneous multichannel sensing

TABLE 4. (Continued)

Information Processing

To transform, to organize, to break down, to combine, to operate on input data or signals

Examples	Required Resource Characteristics
Encoding/Decoding	Numerical computation
Sorting	High volume and/or speed of transactions
Filtering	Simple processing rules or specific programs
Ordering	Parallel or multichannel operations
Merging	Repetitive operations
Analysis	High accuracy or precision
Computation	

Interpreting

To construct, to derive, to translate, to assign meaning to data or signals

Examples	Required Resource Characteristics
Pattern Recognition	Assigning items to a large inclusive class by specific rules
Interpolation	Assigning a narrow range of meanings to inputs
Extrapolation	Estimation of rate of change, acceleration, or higher order derivatives
Prediction	Consideration of specific, predictable, or unambiguous inputs
Association	A minimum number of errors due to expectation or cognitive set
Classification	

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TABLE 4. (Continued)

Decision Making

To select among alternatives, to determine a course of action, to assess the validity of a proposition

Examples	Required Resource Characteristics
Hypothesis Formulation	Dependence upon complex procedures or oprations
Induction/Inference	A large number of differentiations or integrations
Deduction	Deductive reasoning without reference to context
Probability/Contingency Estimation	Prediction based on variable whose nature and weightings are known in advance
Identification and Comparison of Alternatives	Selection among well defined alternatives
Comparison with Standards or Criteria	Invariant decision-making logic
Selection/Choice	Short time lags between scheduled events

Information Storage

To retain or to remain aware of information and, conversely, to recall or to bring forth previously acquired information

Examples	Required Resource Characteristics
Short-Term Memory	Rapid storage (ingestion) of large amounts of data
Long-Term Memory	Long-term storage with total recall
Total Retrieval/Recall	Infallible memory with the precise source of data accurately tagged
Selective Retrieval/Recall	High speed and/or frequent memory search
Purging	Multichannel storage or retrieval Large buffer (immediate memory) capacity Storing of coded or numerical data Rapid and/or complete purging (erasure) of stored data

TABLE 4. (Concluded)

Controlling

To maintain a given level of operation, to adjust and correct for changes in requirements, to adjust for deviations from a prescribed optimum state

Examples	Required Resource Characteristics
Tracking	Generate a variety of movements in response to unpredicted changes
Adjusting	Detect discrepancies
Directing	Apply refined forces
Specific Force Generation	Apply variety of forces in large range of magnitude and duration
Response Latency (Reaction Time)	Respond rapidly and appropriately to apply force in a changing situation

3.0 HUMAN FACTORS AND ROLES

3.1 Initial Considerations

In order to proceed from the Class A generic space station core systems and functions to the determination of function allocations, it seems helpful to answer a number of basic questions about these systems and functions. These questions are listed in Table 5. It should be noted that the user will find that after answering a specific question some of the subsequent answers to questions will be determined as a consequence of the first response. This requires a check for consistency after answering all questions.

3.2 Human and Machine Advantages

After gaining a general idea about the principal allocation approach, the issue of basic human and machine advantages must be reviewed.

One of the most recent papers on the relative capabilities of man and machine [1] discusses techniques for improving human performance in production. The author lists characteristics which tend to favor humans over machines, and vice versa (Table 6). The user, however, must be cautioned to take each item at face value without additional qualifications. Some of these are: Items 1 in top list applies as well to humans, item 9 in the top list seems to be limited to only certain formats and tends to exclude pure qualitative reasoning. Item 1 in the bottom list applies as well to machines. Item 6 of that same list appears somewhat ambiguous in that the exact definition of judgment is rather vague. It certainly would cover deductive reasoning and items like 9 and 10. In simple terms, all systems and functions can

TABLE 5. QUESTIONS FOR DETERMINING THE HUMAN PARTICIPATION FOR EACH FUNCTION [1]

- What is the function under consideration?
- What are the tasks involved in this function?

For each task:

Does this task involve Sensing?
  What part of the Sensing do we give the human operator?
  What part of the Sensing do we give the equipment?

Does the task involve Interpreting?
  What part of the Interpreting do we give the human operator?
  What part of the Interpreting do we give the equipment?

Does the task involve Information Processing?
  What part of the Information Processing do we give the human operator?
  What part of the Information Processing do we give the equipment?

Does the task involve Decision-Making?
  What part of the Decision-Making do we give the human operator?
  What part of the Decision-Making do we give the equipment?

Does the task involve Controlling?
  What part of the Controlling do we give the human operator?
  What part of the Controlling do we give the equipment?

Does the task involve Monitoring?
  What part of the Monitoring do we give the human operator?
  What part of the Monitoring do we give the equipment?

Does the task involve Information Storage?
  What part of the Information Storage do we give the human operator?
  What part of the Information Storage do we give the equipment?

- What is the total hypothesized human operation participation for the function?
- What is the total hypothesized equipment participation for the function?

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TABLE 6. SWAIN'S LIST OF MAN AND MACHINE ADVANTAGES

Ten Characteristics Tending to Favor Machines Over Humans

1. Monitoring men or other machines.
2. Performance of routine, repetitive, precise tasks.
3. Responding quickly to control signals.
4. Exerting large amounts of force smoothly and precisely.
5. Storing and recalling large amounts of precise data for short periods of time.
6. Computing ability.
7. Sensitivity to stimuli.
8. Handling of highly complex operations (i.e., doing many different things at once).
9. Deductive reasoning ability.
10. Insensitivity to extraneous factors.

Fourteen Characteristics Tending to Favor Humans Over Machines

1. Ability to detect certain forms of energy.
2. Sensitivity to a wide variety of stimuli.
3. Ability to perceive patterns and generalize about them.
4. Ability to detect signals (including patterns) in high noise environments.
5. Ability to store large amounts of information for long periods and to remember relevant facts at the appropriate time.
6. Ability to use judgment.
7. Ability to improvise and adopt flexible procedures.
8. Ability to handle low probability alternative (i.e., unexpected events).
9. Ability to arrive at new and completely different solutions to problems.
10. Ability to profit from experience.
11. Ability to track in a wide variety of situations.
12. Ability to perform fine manipulations.
13. Ability to perform when overloaded.
14. Ability to reason inductively.

be reduced to three disciplines: sensing, computing, and actuating. The decision, in each individual case, is then to decide between human, machine, and participating activity between the two.

A question to be answered at this time relates to infrequent and to unlikely functions that may occur. Humans may forget to perform infrequent functions or have lost the skill to perform them. On the other hand, it may be quite uneconomical to automate them. Unlikely functions, however, seem to be best performed by humans if they are capable of doing them. Based on these reasons, these items are not included in the table.

3.3 General Roles of Humans in a System and Development of the Role of Humans

There is a distinction between the role of humans and the function of humans. The role must be defined before specific functions are allocated. Table 7b lists questions under "Development of the Role of Man," the answers to which define the basic role of humans in a system listed in Table 7a. The specifics of this role are then modified during functions allocation.

TABLE 7a. GENERAL ROLES OF MAN IN A SYSTEM [1]

- Contributing capabilities not possible with an automatic system
  - Identifying goals
  - Developing plans
- Operation of system equipment (primary or back-up)
  - Process control
  - Reconfiguration of system equipment
  - Intervention in automated functions
- Monitoring system equipment
- Diagnosing system malfunctions

TABLE 7b. DEVELOPMENT OF THE ROLE OF MAN

- Can man's unique capabilities be significant in the attainment of the system goals?
  - Man has the ability to learn
  - Man has the capacity for creative problem solving
- What system performance could be implemented by man?
- If a role for man is justified because of his unique capabilities (question 1) or primary performance activities (question 2), what other performance should be assigned to him to take advantage of his utilitarian capabilities?
- Will man's unique limitations constrain his use in the system?
  - Man has certain physical characteristics
  - Man has physiological needs
  - Man has psychological needs
- Will man be local or remote to the primary system?

TABLE 8. CRITERIA THAT DEFINE UNIQUE HUMAN CAPABILITIES [1]

Human participation in the performance of a function is mandatory when that function requires one or more of the following capabilities. • Develop a Strategy. Man's inclusion is mandatory when: – Operations cannot be reduced to preset procedures – The form and content of all inputs and outputs cannot be specified or predicted * – The relationship between inputs and outputs may require restructuring during task performance. • Integrate a Large Amount of Information. Man must be included in the accomplishment of a function when: – Signals must be detected against a noise background * – Patterns of information and trends must be extracted from several sources. • Make and Report Unique Observations. Man must be included when a function requires that observation be made of: – The performance of others – The performance of self * – Ephemeral events. • Assign Meaning and Value to Events. Man must be included when performance of a system or function requires that meaning and relative values be assigned to events.

3.4 Unique Human Capabilities

In defining unique human capabilities it has to be recognized that "unique" is often only a temporary characteristic and depends on the state-of-the-art of any applicable technology. What is considered unique today may not be any more unique at a later time. Within the criteria that define unique human capabilities (Table 8), there are at least three capabilities which may soon be automated. These are marked by asterisks in the table.

3.5 Unique Human Limitations

In contrast to the unique human capabilities which often will prove to be strongly dependent on the future time period under consideration, the unique human limitations listed in Tables 9 and 10 are rather fixed and permanent and are not very accessible to training and learning. This does not consider yet the possibility of human-machine hybrids where direct interconnections exist between human senses (or brain) with appropriate machines which would expand human capabilities or reduce human limitations [10]. Research in these areas is under way.

TABLE 9. A FEW OF MAN'S UNIQUE LIMITATIONS [1]

1. Man comes in only a single model. From a design point of view, man can be integrated into the system concept only as a complete "unit" with variable physical characteristics: dimensions, weight, and strength.

2. Man has certain performance limitations from the standpoint of such things as sensitivity, reaction time, number of information channels, rate of response, and tolerance to stress.

3. Man's performance has an associated cost. One pays a price for providing and maintaining reliable human performance. These costs are measurable in terms of: selection; training; maintenance of proficiency; manuals, handbooks, instructions, and job aids; biological support; and management. These costs are not always evident to the designer until a system is operational.

4. Man has physiological needs. Human performance deteriorates rapidly when physiological needs for nourishment, sleep, comfort, and health are not satisfied.

5. Man has psychological needs. Man's performance deteriorates over prolonged periods of high stress or inactivity. Human performance also changes significantly because of such psychological variables as motivation, frustration, conflict, and fear.

TABLE 10. CRITERIA THAT LIMIT OR PRECLUDE HUMAN PARTICIPATION IN A SYSTEM FUNCTION [1]

Consideration should be given to the exclusion of man in performing a function when one or more of the criteria below apply.

- Force Application. Large, precise, or extended applications of force preclude the use of man. Man's instantaneous peak force is limited to a mean force of 3000 Newtons.

- Response to Stimuli/Signals. The human operator experiences a finite lag between the onset of a stimulus and the ability to make a response to it. This lag varies from a mean of 100 msec for auditory stimuli and approximately 120 msec for visual stimuli, to lags of 1 sec for responses involving a choice among alternatives.

- Precise Calibration and Measurement. Human operators are incapable of making precise measurements and calibrations.

- Reliable Response. Because of the variability of human response, man should be precluded from performing functions which require the unvarying repetition of one or more responses.

- Time Sharing. Under most circumstances man acts as a single-channel information processor and should ordinarily be precluded from performing multiple time-shared tasks.

- Continuous Performance. Man should be precluded from performing functions which cannot be interrupted or which require sustained attention for long periods of time (e.g., in excess of 20 min).

- Detection of Low Frequent Events. The operator should be precluded from performing functions which require the detection of rarely occurring stimuli, events, or conditions.

3.6 Human Effectiveness in Performing Functions

In order to evaluate each generic system and function of a space station, twelve specific parameters are suggested from which a matrix can be constructed listing the functions in a column and the parameters in a row. The parameters are listed in Table 11 with their descriptions.

TABLE 11. PARAMETERS FOR EVALUATING EFFECTIVENESS OF MAN IN PERFORMING FUNCTIONS [2]

Feasibility	The likelihood that man can perform the designated function successfully on orbit or on site with necessary tools. Scale: low, medium, or high.
Utility	Usefulness of man doing the task instead of with automatic machines. Scale: low, medium, or high.
Location of Man	The physical location of man performing the function. Options: on ground, orbit, or site.
Level of Manned Interaction	Degree to which man can participate in performing the function. Scale: low, medium, or high.
Frequency or Duration	The number of times the function is performed during a mission or the length of time for an occurrence.
Technical Risk	The technical risk incurred by performing the function using man. Scale: low, medium, or high.
Time Phasing	Period in program when a function is to be performed.
Common Aspects	Characteristics of function which are common to several discipline areas and can be performed with similar operations.
Unique Aspects	Characteristics of function which require that only man or machine perform work.
Costs	Coarse estimate of additional costs to incorporate manned performance of function. Scale: low, medium, or high.
Effectiveness Comparison	Estimate of the relative effectiveness of performing the function by man and by machine. Scale: good, medium, or poor.
Recommended Method	Estimate of the best method for performing the function using man, machine, or interactive system.

3.7 Human Factors Development During Systems Definition

The importance of developing the human role as early as during the mission analysis phase is emphasized in Reference 3. This has to be followed by the function allocation, the definition of human factors engineering requirements, and finally, result in an optimum human-machine interface in the full scale development phase (Table 12).

TABLE 12. PRINCIPAL HUMAN FACTORS DEFINITIONS DURING MAJOR SYSTEM DEVELOPMENT PHASES [3]

System Development Phase	Human Factors R&D Principal Product	Potential System Design Effects
Mission Analysis Phase (Pre-Phase A)	Development of the Role of Man	(a) Maximum mission flexibility (b) Maximum crew acceptance (c) Minimal crew size and cost (d) System recoverability
Concept Development Phase (Phase A)	Allocation of System Functions to Man	(a) Balanced automation (b) Mission sustainability/endurance (c) Optimum response to emergencies (d) Responsiveness to change
Demonstration and Validation Phase (Phase B)	Task Analysis and Determination of Human Factors Engineering Requirements	(a) High quality decision making (b) Productive and satisfying job designs (c) Minimal training costs (d) Minimal maintenance costs (e) Minimal retrofit and redesign
Full-Scale Development Phase (Phase C, D)	Design of the Optimal Man-Machine Interfaces	(a) Minimal response delays (b) Optimal accuracy/reduced errors (c) Optimal survivability (d) Optimal user compatibility

4.0 THE ROLE OF AUTOMATION

4.1 Current State of Automation [12]

The current state of automation is limited to relatively-simple, pre-programmed tasks with little or no machine intelligence and very restricted sensing of environments. For the more complex and dynamic environment associated with space applications, it is still necessary to incorporate man in the control loop. In order to achieve the ambitious goals of the space program in areas such as space station and long-life reserviceable spacecraft, it is essential to reduce direct human control of the robotic systems. This reduction can most naturally occur over a four-phase development process.

The first phase is to develop the required system with man in the loop to provide control and problem solving functions. The second phase of robotic system evolution is to extract the man from the primary control loop to assume a supervisory role. In this role, the operator will perform the functions of planning out a sequence of tasks to achieve a specific goal. In the third phase, the individual will be extracted one more level. In this phase, the operator will perform the function of establishing intermediate goals for the robotic system. The robotic system will perform the functions associated with breaking down the specific goals into individual tasks to be performed. The final phase of robotic evaluation is the development of a fully-autonomous robotic system.

4.2 Automation Guidelines for Space Stations

General guidelines on when and how to automate space station systems and functions as well as pitfalls of automation are given in Table 13.

4.3 Technical Feasibility of Automation

In order to decide on the technical feasibility of automating a specific system or function, a number of questions need to be answered. These are listed in Table 14. For better orientation about the various levels of automation, Table 15 has been adapted from Reference 11 and lists five distinct technological levels of increasing complexity.

4.4 Economic Feasibility of Automation

A number of questions have to be answered as to the economic feasibility of automation (Table 16). In establishing system cost this must include the cost of acquiring, automatically maintaining, and operating a fully automatic system. The cost of including one or more human operators or maintainers entails the aggregate costs of personnel selection, training, life support, staffing, attrition, and management, and the provision of supporting documents, manuals, job aids, and training devices.

4.5 Total Automation

In certain instances total automation of specific systems and functions will be necessary. In order to define these systems and functions, a set of criteria has been developed and is presented in Table 17. The reference charts shown in this table can be found in the appendix of this report.

TABLE 13. GENERAL AUTOMATION GUIDELINES FOR SPACE STATIONS [4]

When to Automate:

To reduce excessive workload

1. Consider automating to avoid perceptual saturation.
2. Consider automating to reduce concurrent tasks.
3. Consider automating tasks on compressed time-lines.
4. Consider automating to avoid astronaut bandwidth limitations.
5. Consider automating to eliminate or consolidate small-scale operations.

To reduce errors

6. Consider automating routine tasks.
7. Consider automating memorization tasks.
8. Consider automating sequential and time tasks.
9. Consider automating seldom-performed tasks.
10. Consider automating monitoring tasks.
11. Consider automating tasks astronauts find boring and unmotivating.

To improve performance

12. Consider automating precision tasks.
13. Consider automating emergency-prevention devices.
14. Consider automating complex mathematical or logical tasks.

To add new capability

15. Consider automating complex tasks that must be performed rapidly.

How to Automate:

Control Tasks

16. Design space station controls and displays to be compatible with astronaut's mental representations of the tasks.
17. Use automation to eliminate peak task demands.
18. Provide optional capability for manual operation of the system.

Monitoring tasks

19. Keep false-alarm rate low
20. Provide operationally-relevant information.
21. Allow for astronaut query.
22. Design alarms to indicate the extent of emergencies.
23. Expose astronauts to all alerts and to important combinations.

Pitfalls of Automation

24. Beware of reliability and maintenance problems in complex systems.
25. Beware of unnecessary use of automation.
26. Beware of the lack of astronaut acceptance.
27. Beware of substitution of emergency backup systems for main systems.
28. Beware of the loss of astronaut's manual skills.
29. Beware of increased training requirements.
30. Beware of failure modes for complex systems.
31. Beware of system inflexibility or unmodifiability.
32. Beware of unknowns.

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TABLE 14. CRITERIA FOR ASSESSING THE TECHNICAL FEASIBILITY OF AUTOMATION [1]

A system can be automated if the following criteria can be satisfied.

- Component Availability. Are the necessary hardware and software components required by the system available off-the-shelf?
- Development Time. If components are not readily available off-the-shelf, can needed components be developed within the scheduled life-cycle development limit for the system or can that limit be revised to permit development and testing?
- Predictability. Can system events (i.e., mission events and system failure modes) be predicted and handled by automation?
- Reliability. Is the expected reliability of the proposed system configuration adequate to meet system performance requirements?
- Failure. Can the consequences of expected system failures be compensated for by automatic back-up or otherwise prevented from exceeding acceptable limits?
- Safety. Can adequate safeguards against dangers to health be fully automated?

TABLE 15. THE FIVE LEVELS OF AUTOMATION, AS DEVELOPED BY MERTES AND JENNEY [11]

Level I Automation of Computational Aids

At this order of automation, repetitive computation and routine data processing tasks, and maintenance of the system data base, are allocated to machines.

Level II Automation of Aids to Decision Making

At this level, machines are assigned to more sophisticated data processing tasks. Machines begin to function as a means of alerting man to the need for a decision and providing him with data to assist his decision making.

Level III Automation of Decision Making

At this level, many decision-making tasks, particularly those of a routine and repetitive nature, are assigned to machines.

Level IV Automation of Communications

At this level, the machine replaces man in the space-ground communication loop for routine relay of information. Man is responsible for communications of a special or emergency nature.

Level V – Full Automation

This level represents a system in which man has no direct responsibility for regulation and control. Man's role has become that of a system monitor and manager. He controls a complex of automated resources which, in turn, control the space station.

NOTES:

These levels were developed by Mertes and Jenney [11] as a result of a study on automation applications in air traffic control (ATC) tasks, and were derived from an analysis of 265 generic tasks.

The authors examined the ATC tasks within each level for corresponding automation within existing systems in order to determine how tasks combined to form functional groups.

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TABLE 16. CRITERIA FOR ASSESSING THE ECONOMIC FEASIBILITY OF AUTOMATION [9]

A system can be automated within economic constraints if it meets the following criteria:

- Cost-Effectiveness. Will automation of the system be more cost-effective than the use of a human operator to perform one or more system functions? This assumes that inclusion of the operator is not precluded for reasons of life support or human performance limitations.
- Funding. Can all necessary costs of development, design, testing, installation, and automation be covered by known financial resources?

TABLE 17. CRITERIA FOR TOTAL AUTOMATION [9]

A system should be fully automated when a statement of its requirements or its present configuration meets one or more of the following criteria:

- Regulation or Policy. A system must be automated when regulation or public policy so dictate. This assumes that automation can be accomplished with available resour[illegible] known technology.
- Environmental Factors. A system must be automated when any form of human [illegible] is precluded because the system or its environment either will not support human [illegible] create products or conditions that would endanger it. This assumes that an adequate life support system cannot be developed and that man cannot be remoted to a safe environment to perform essential system functions. Environmental criteria include:
  - Uncontained radiation (see Chart A-1)
  - Heat (see Chart A-2 to A-4)
  - Noise (see Chart A-5)
  - Atmospheric pressure and sudden pressure change (see Chart A-6)
  - Chemical or biological substances (see Chart A-7)
  - Vibration (see Chart A-8).
- System Requirements and Constraints. A system must be automated when its performance requirements exceed or fall outside of the range of human capability. Performance requirements in the following areas may make automation mandatory. They are best expressed as a series of questions having qualitative or quantitative answers.
  - Controlling: Do system requirements demand operational response to be made at speeds which cannot be attained or maintained by a human operator? Does the system require that adjustments be made which are too precise for the human operator to make?
  - Monitoring: Does the system require the human operator to maintain a state of alertness or preparation which is beyond the operator's normal limits? (Chart A-16)
  - Sensing: Are there stimuli required by the system which are beyond the capability of human operators to perceive them? (Chart A-17 and A-18)
  - Information processing: Are there information processing tasks, such as computations, which require performance beyond the normal range of the human operator? (Charts A-14 and A-15)
  - Interpretation: Does the system require performance in areas such as classification or extrapolation (calculating accelerations) which are not possible for the human operator to perform within the limits of the system?
  - Information storage: Do system requirements demand that the operator be able to store and retrieve large amounts of information in ways that are beyond human capabilities?
  - Decision-making: Does the system require that the operator determine a course of action or make a selection from among existing procedural options in a shorter time than the normal operator is capable of making such determinations? (Charts A-11 and A-12)

5.0 APPENDIX

Data on Human Capabilities and Limitations

The following data have been extracted from various sources as indicated. The references listed at the end of this report can provide additional information if desired.

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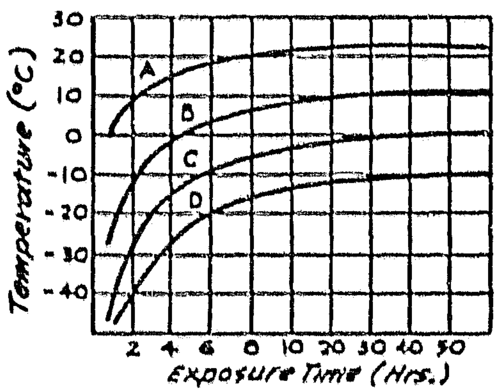
A-1. EFFECTS OF ACUTE WHOLE-BODY EXTERNAL RADIATION EXPOSURE
(From Woodson, 1981)

0 25 rems	25-100 rems	100-200 rems	200-300 rems	300-600 rems	600 rems or more
Immediate Effects					
No detectable clinical effects	Slight transient reductions in lymphocytes and neutrophils	Nausea and fatigue with possible vomiting above 125 rems *	Nausea and vomiting on first day	Nausea, vomiting, and diarrhea in first few hours	Nausea, vomiting, and diarrhea in first few hours
	Disabling sickness not common, exposed individuals should be able to proceed with usual duties	Reduction in lymphocytes and neutrophils with delayed recovery	Latent period up to 2 weeks or perhaps longer	Latent period with no definite symptoms, perhaps as long as 1 week	Short latent period with no definite symptoms in some cases during first week
Delayed Effects					
Delayed effects may occur	Delayed effects possible, but serious effects on average individual very improbable	Delayed effects may shorten life expectancy in the order of 1%	Following latent period, the following symptoms appear but are not severe loss of appetite, and general malaise, sore throat, pallor, petechiae, diarrhea, moderate emaciation	Epilation, loss of appetite, general malaise, and fever during second week, followed by hemorrhage, purpura, petechiae, inflammation of mouth and throat, diarrhea, and emaciation in the third week	Diarrhea, hemorrhage, purpura, inflammation of mouth and throat, fever toward end of first week Rapid emaciation and death as early as the second week, with eventual death of up to 100% of exposed individuals
			Recovery likely in about 3 months unless complicated by poor previous health or superimposed injuries or infections	Some deaths in 2 to 6 weeks. Possible eventual death to 50% of the exposed individuals for about 500 rems	

A-2. TOLERANCE TO LOW TEMPERATURES
(From Woodson, 1981)



Legend:

A--1-clo (light coveralls)
B--2-clo (woolen underwear, coveralls, and jacket)
C--3-clo (intermediate-weight flight clothing)
D--4-clo (heavy flight clothing)

Subjects were seated and performing light work. Air velocity, approximately 200 ft/min; barometric pressure, 1 atm.

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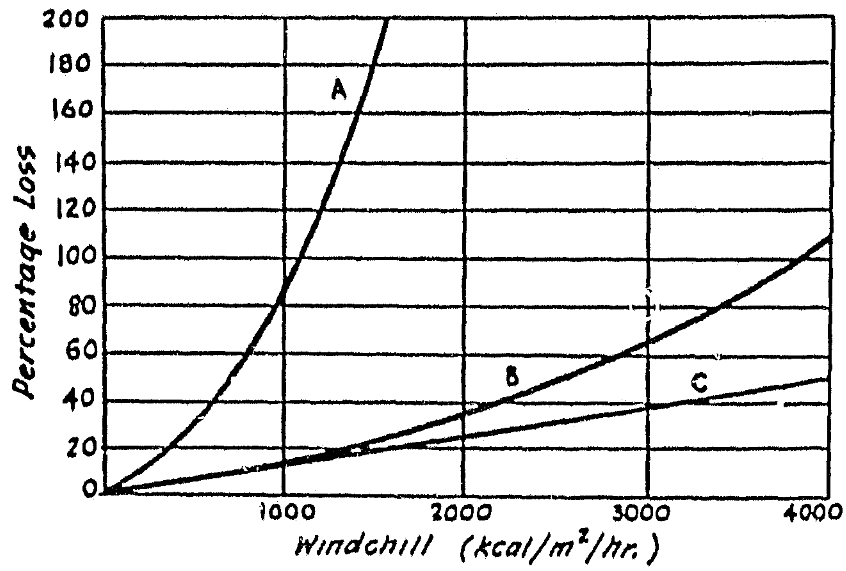
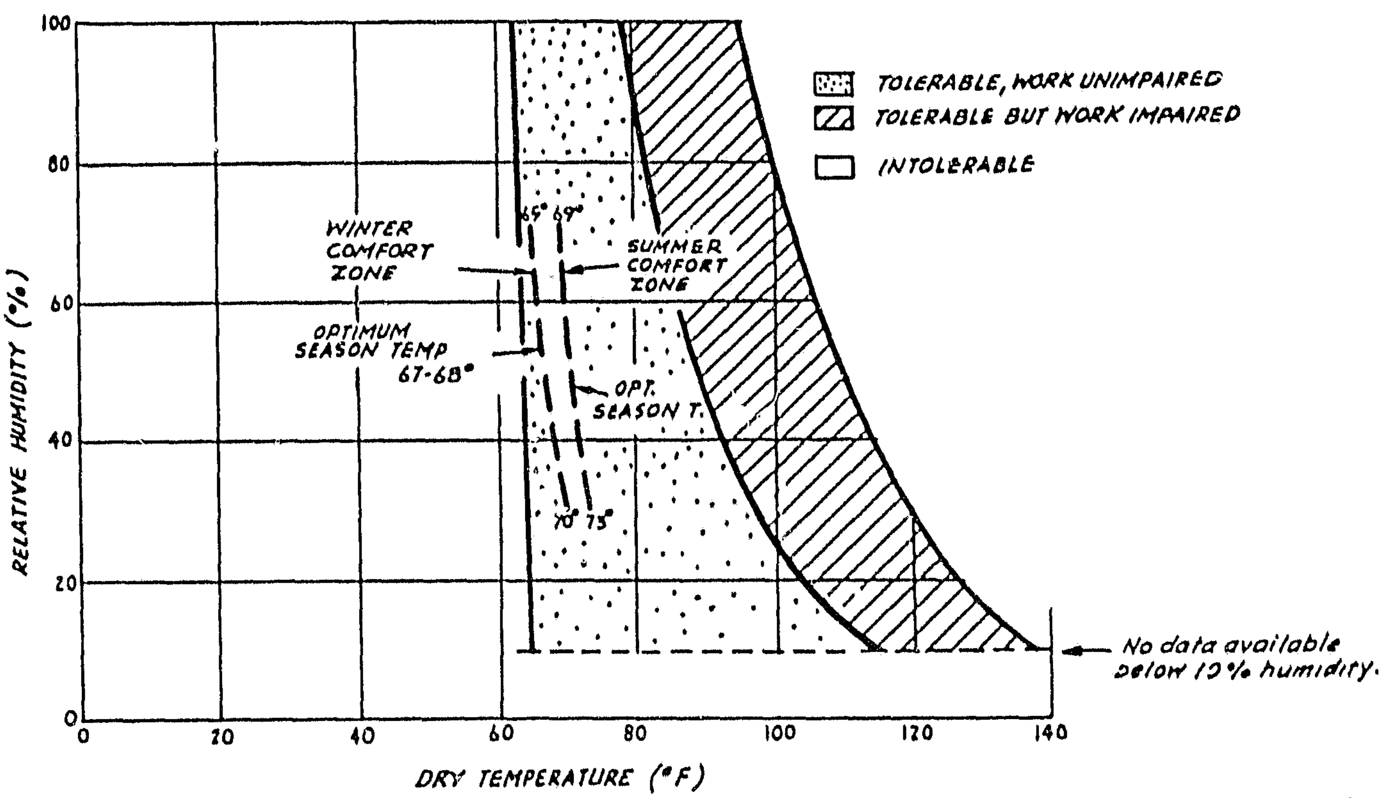
A-3. EFFECTS OF COLD ON SELECTED TASK PERFORMANCES
(Ref. 1)



Legend:

A--tactile sensitivity, bare hand
B--simple visual reaction time
C--manual skill

A-4. TEMPERATURE-HUMIDITY TOLERABILITY
(WITH CONVENTIONAL CLOTHING)
(From Woodson, 1981)



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A-5. POTENTIAL EFFECTS OF HIGH NOISE LEVELS
(From Woodson, 1981)

When noise levels exceed 100 dB, potentially serious consequences occur, as shown below.

Noise Level, dB	Spectrum	Duration	Effects
105	Jet engine	2 min	Reduced visual acuity, stereoscopic acuity, and near-point accommodation and permanent hearing loss when exposure continues over a long period (months)
110	Machinery noise	8 hr	Chronic fatigue and digestive disorders
120	Broadband	1 hr	Loss of equilibrium
150	1-100 Hz	2 min	Reduced visual acuity, chest-wall vibration, changes in respiratory rhythm, and a "gagging" sensation*

*Subjects were wearing so-called protective aids to prevent hearing loss.

A-6. EFFECTS OF HIGH AND LOW OXYGEN LEVELS
(From Woodson, 1981)

Partial Pressure of Oxygen, mm of Hg	Percent of Oxygen in Dry Air at Sea Level Pressure	Effect
		Oxygen Excess
456	60	Onset of oxygen poisoning after some hours.
167	22	Limit set in RN to control fire hazard in charcoal filters in nuclear submarines
		Normal
160	21	Normal atmospheric level
		Oxygen Lack
137	18	Accepted limit of alertness. Loss of night vision Earliest sign—dilation of the pupils.
114	15	Performance seriously impaired. Hallucinations, excitation, apathy.
100	13	Coordination impaired. Emotional upset.
84	11	Paralysis, loss of memory. Irreversible unconsciousness.
46	6	Death before symptoms apparent.

Note The effect of falling oxygen is insidious, because it dulls the brain and prevents realization of danger

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A-7. SKIN REACTION TO CHEMICAL SUBSTANCES
(From Woodson, 1981)

The table below presents a partial list of chemical substances and their action on the skin.

Agent	Reaction
Acids:	
Acetic	Dermatitis and ulcers
Carbolic	Irritation and erosion, eczema, and anesthesia
Chromic	Ulcers (chrome holes on the skin), inflammation, and perforation of the nasal septum
Hydrochloric	Irritation and ulceration
Hydrofluoric	Severe burning, erosion ulcers, and blisters
Lactic	Ulcers (if strong solution)
Nitric	Severe burns and ulcers
Oxalic	Local caustic action on the skin
Sulfuric	Corrosive action on the skin and severe inflammation of the mucous membranes
Alkalis:	
Calcium cyanamide	Irritation and ulceration
Calcium oxide	Dermatitis, burns, and ulcers
Potassium hydroxide	Severe burning, persistent ulcers, and loss of fingernails
Sodium hydroxide	
Sodium silicate	Thickening of the skin and ulcers on the fingers
Sodium or potassium cyanide	Blisters and ulcers
Salts:	
Antimony and its compounds	Irritation and eczematous eruptions
Arsenic	Skin darkening, perforation of the nasal septum, eczema around the mouth and nose, and possible loss of nails or hair
Barium	Eczema and cyanosis of skin
Bromine	Brownish stains and skin erruptions
Chromium (hexavalent compounds)	Chrome holes on the skin, perforation of the nasal septum, and eczematous eruptions
Mercury compounds	Corrosion and irritation and mercurial eczema
Sodium	Burns and ulcers
Zinc chloride	Ulcers of the skin and nasal septum
Solvents:	
Acetone	Dry (defatted) skin
Benzene	Dry (defatted) skin
Carbon disulfide	Dry (defatted) skin
Chlorinated phenols	Severe eruptions
Petroleum distillates	Acne and epithelioma
Trichlorethylene	Dry, cracked skin
Turpentine	Red, blistered skin and eczema
Dyes:	
Chlorinated compounds	Blisterlike eruptions
Dinitrochlorobenzene	Blisterlike eruptions
Nitro and nitroso compounds	Red skin and eczematous eruptions
Phenyl hydrazine	Blisterlike skin eruptions
Insecticides:	
Chlorophenols	Red skin, and blisters
Creosote	Pustular eczema, warts, and epithelioma
Fluorides	Severe burns and dermatitis
Pyrethrum	Red skin, blisters, and pimples
Rotenone	Red skin and blisters
Resins:	
Coal tar, pitch, and asphalt	Acute dermatitis, acne, inflammation, epitheliomatous cancer, eczema, and ulcers
Synthetics, e.g., phenol-formaldehyde	Extremely red and itchy skin
Synthetic waxes, e.g., chloronaphthalenes and chlorodiphenyls	Dermatitis and acne

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A-8. EFFECTS OF VIBRATION ON HUMAN PERFORMANCE
(From Woodson, 1981)

Vibration Conditions	Measures	Effect	Source
		Biodynamic Mechanisms	
$\pm$0.15–0.35 *g*, at 0.9–6.5 Hz, low amplitude	Whole body vertical vibration, hand tremor, body equilibrium, foot pressure	Foot pressure constancy impaired at 3.5 to 6.5 Hz, error increase with intensity; no residual effects	Schmitz, Simons, and Boettcher, 1960
$\pm$*ng*, $\pm$ *ng*, for ½ hr	Body sway equilibrium	No effects	Hornick, Boettcher, and Simons 1961
$\pm$*g*, 2–20 Hz (intensities = ¼ short-term tolerance limits)	Control of pitch and roll of a chair	Wide individual differences; decrement between 3 and 12 Hz, worst at 6 Hz	Coermann, Magid, and Lange, 1962
$\pm$*g*, at 0, 2, 5, and 8 Hz	Orientation (orienting body position to face targets at 15, 30, and 60° from reference plane)	Only small decrement in accuracy; mean error < 0.5°	Ayoub, c. 1969
$\pm$0.03 – $\pm$0.41 *g*, at 0, 3, 5, and 8 Hz	Leg muscular power (on bicycle ergometer)	No effects	Harrison, 1969
Various peak-to-peak accelerations at 1 Hz with 3 Hz, and 2 Hz with 6 Hz	Arm-hand steadiness	Positional errors significantly related to rms and frequency of vibration; 90% of error was periodic; 1 Hz with 3-Hz combination produced larger error; small (0.5–1 *g*) differences in acceleration had no effect	Clarke et al., 1965
		Psychomotor Performance	
+0.25 *g*, at 2.4–9.5 Hz	Time to pick up markers and place in small circular areas	Completion time worst at 3.4 and 4.8 Hz	Guignard and Irving, 1960
+0.5 rms *g*, at 2–30 Hz (13-Hz peak power)	Digital decimal input with push button, toggle switch, rotary switch, and thumbwheel controls	Accuracy unaffected; insert times increased by 4%; push buttons and toggle switches were most rapidly used, with the former preferred; thumbwheels were most accurate	Dean et al., 1967
0, 0.2, 0.4, 0.6, and 0.8 rms *g*, for 5 min	Same	No effects for 0.2 and 0.4 rms *g*; significant increase in insert time for 0.6 and 0.8 rms *g*; speed: push buttons >*rotary switches > thumbwheels; error rate: push buttons highest and thumbwheels lowest for high intensity vibrations	Dean, Farrell, and Hitt, 1967
$\pm$*g*, and $\pm$*g*, at 0.33 and 0.80 Hz at amplitude of $\pm$6.3 and $\pm$7.0 in	Nut and bolt assembly and disassembly; placement of probe through various sized holes	No effects at 0.33 Hz; time required increased by 30% at 0.80 Hz with no increase in accuracy	Seeman and Williams, 1966
		Speech Intelligibility	
$\pm$*g*, at 10, 20, 30, 40, and 50 Hz	Intelligibility	Most effect at 10 and 20 Hz	Nixon, 1962
0.5 *g*, sinusoidal at 6 Hz; 0.75 *g*, at 4 and 8 Hz; 1.0 *g*, at 2–20 Hz	Intelligibility and quality	No effect on intelligibility at 65 dB; "quality" poorer than control condition	Nixon and Sommer, 1963
		Audition	
5-Hz sinusoidal, 5-Hz random amplitude, 4- to 12-Hz random frequency	Frequency (pitch) change (1200 for 1600 Hz) at 86-dB tones of 0.25-s duration every second—detection	No effect	Weisz, Goddard, and Allen 1965
$\pm$*g*,	1200 Hz at 86 dB presented every 0.25 s for 1 s against a 74-dB, 30- to 3000-Hz white noise, pitch change at 86 dB (1600 for 1200 Hz)—detection	No effect	Holland, 1966
+1 *g*, $\pm$0.7 *g*, at 15 Hz (amplitude 0.036 in) for 30 min	TTS determined as function of vibration and noise versus noise alone (acoustical frequencies from 250–6000 Hz)	Extremely small vibration effect at low tone frequencies only	Guignard and Coles, 1965
		Higher Mental Processes	
$\pm$0.15 – 0.35 *g*, at 2.5 and 3.5 Hz	Mental addition	No effect	Schmitz, Simons, and Boettcher, 1960
$\pm$*g*, at 5, 7, and 11 Hz	Pattern matching and discrimination	No effect	Buckhout, 1964
0.40 rms *g*, random vibration	Navigational tasks in simulated low-altitude, high-speed flight	No effect	Schohan, Rawson, and Soliday, 1965; Soliday and Schohan, 1965
No vibration, no noise, no vibration; noise only, vibration plus noise, postvibration +4.0 *g*, at 70 Hz	Continuous counting at a given rate	Decrement, especially during 5–7 min of exposure; residual effects noted; 70% of decrement attributed to vibration (30% to noise) Ss over 36 showed greater decrement	Ioseliani, 1967

*Symbol > here indicates faster than.

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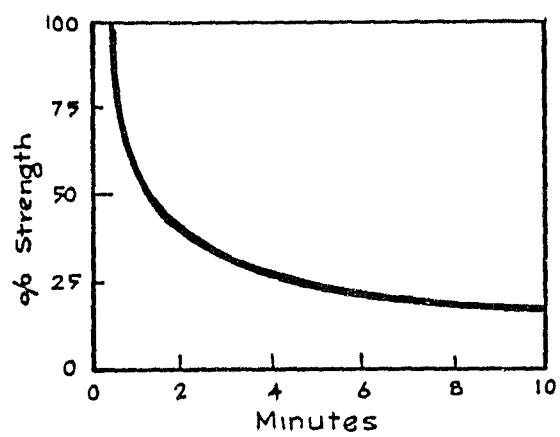
A-9. HEIGHT/WEIGHT RANGES OF U.S. MALES/FEMALES (CAUCASIAN)
(From Van Cott and Kinkade, 1972)

	Male				Female			
	Height (in.)		Weight (lb)		Height (in.)		Weight (lb)	
Age (yr)	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	29.7	1.1	23	3	29.3	1.0	21	3
2	34.5	1.2	28	3	34.1	1.2	27	3
3	37.8	1.3	32	3	37.5	1.4	31	4
4	40.8	1.9	37	5	40.6	1.6	36	5
5	43.7	2.0	42	5	43.8	1.7	41	5
6	46.1	2.1	47	6	45.7	1.9	45	5
7	48.2	2.2	54	7	47.9	2.0	50	7
8	50.4	2.3	60	8	50.3	2.2	58	11
9	52.8	2.4	66	8	52.1	2.3	64	11
10	54.5	2.5	73	10	54.6	2.5	72	14
11	56.8	2.6	82	11	57.1	2.6	82	18
12	58.3	2.9	87	12	59.6	2.7	93	18
13	60.7	3.2	99	13	61.4	2.6	102	18
14	63.6	3.2	113	15	62.8	2.5	112	19
15	66.3	3.1	128	16	63.4	2.4	117	20
16	67.7	2.8	137	16	63.9	2.2	120	21
17	68.3	2.6	143	19	64.1	2.2	122	19
18	68.5	2.6	149	20	64.1	2.3	123	17
19	68.6	2.6	153	21	64.1	2.3	124	17
20–24	68.7	2.6	158	23	64.0	2.4	125	19
25–29	68.7	2.6	163	24	63.7	2.5	127	21
30–34	68.5	2.6	165	25	63.6	2.4	130	24
35–39	68.4	2.6	166	25	63.4	2.4	136	25
40–49	68.0	2.6	167	25	63.2	2.4	142	27
50–59	67.3	2.6	165	25	62.8	2.4	148	28
60–69	66.8	2.4	162	24	62.2	2.4	146	28
70–79	66.5	2.2	157	24	61.8	2.2	144	27
80–89	66.1	2.2	151	24				

A-10. HUMAN PHYSICAL STRENGTH AND ENDURANCE
(From Woodson, 1981)



Typical endurance time in relation to force requirements.

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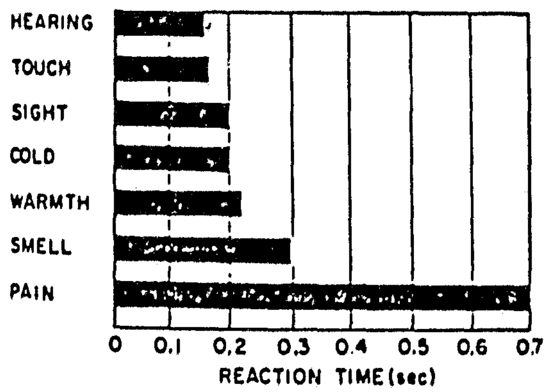
A-11. REACTION TIME COMPARISONS OF SENSORY INPUT CHANNELS
(From Woodson, 1981)



Note: Signals should not occur at rates faster than about two per second unless some means are provided for anticipating the signal. Avoid alerting periods shorter than 0.1 s.

A-12. EFFECT OF NUMBER OF RESPONSE CHOICES
(From Woodson, 1981)

As one might expect, when the number of response choices increases, the reaction time is lengthened. The table below illustrates this point.

Number of Choices	Mean Reaction Time, s
1	0.20
2	0.35
3	0.40
4	0.45
5	0.50
6	0.55
7	0.60
8	0.60
9	0.65
10	0.65

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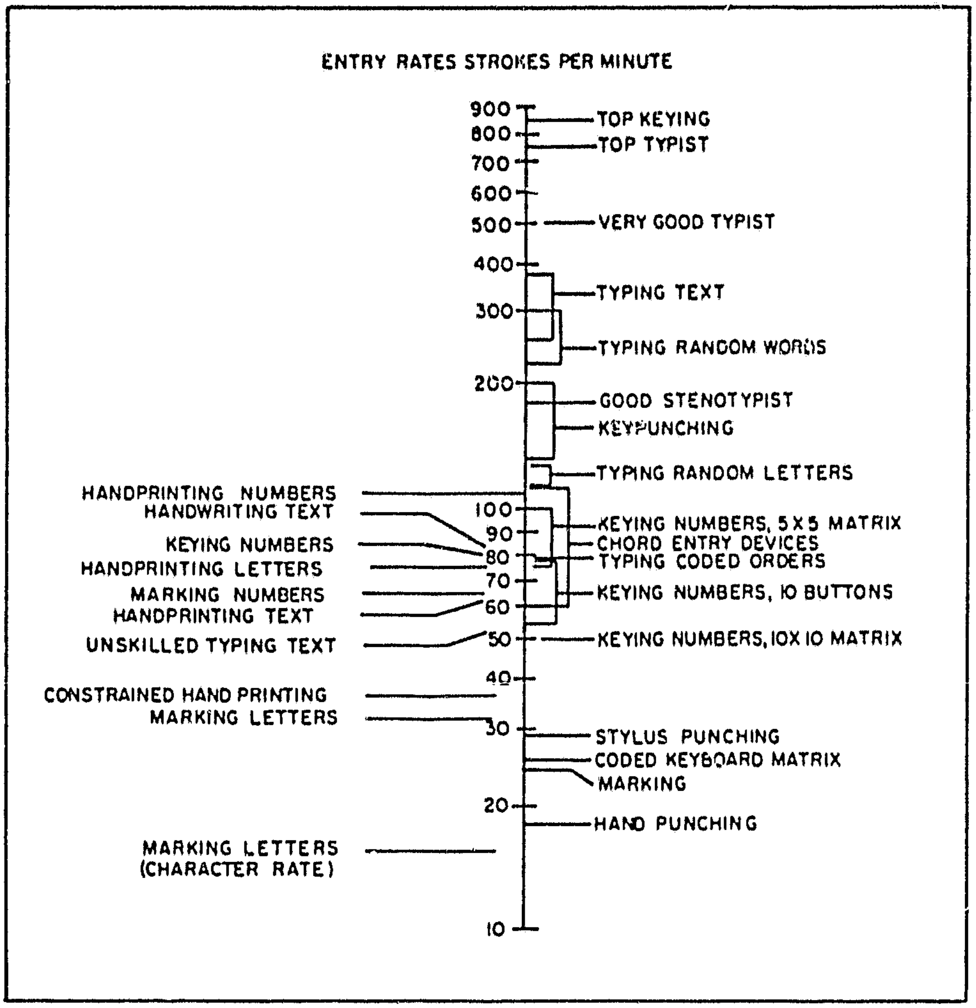
A-13. REPRESENTATIVE MANUAL ENTRY RATES
(Adapted from Devoe, 1967)



A-14. SENSORY CHANNEL CAPACITY FOR MULTIDIMENSIONAL STIMULI
(From Van Cott and Kinkade, 1972)

Stimulus dimension	Channel capacity (bits)	Discrim-inable categories	Investigator
Size, brightness, and hue (varied together).	4.1*	18	Eriksen (1954).
Frequency, intensity, rate of interruption, on-time fraction, total duration, and spatial location.	7.2	150	Pollack & Ficks (1954).
Colors of equal luminance	3.6	13	Halsey & Chapanis (1954).
Loudness and pitch	3.1	9	Pollack (1953).
Position of points in a square (no grid).	4.6	24	Klemmer & Frick (1953).

* Note: The capacity of each dimension separately was approximately 2.7 bits.

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A-15. SENSORY CHANNEL CAPACITY FOR DIFFERENT UNIDIMENSIONAL STIMULI

(From Van Cott and Kinkade, 1972)

Sense	Stimulus dimension	Channel capacity (bits)	Discriminable categories	Investigator
Vision	Dot position (in space)	3.25	10	Hake & Garner (1951).
	Dot position (in space)	3.2	10	Coonan & Klemmer (in Miller, 1956).
	Size of squares	2.2	5	Eriksen & Hake (1955).
	Dominant wavelength	3.1	9	Eriksen & Hake (1955).
	Luminance	2.3	5	Eriksen & Hake (1955).
	Area	2.6	6	Pollack (in Miller, 1956).
	Line length	2.6–3.0	7–8	Pollack (in Miller, 1956).
	Direction of line inclination.	2.8–3.3	7–11	Pollack (in Miller, 1956).
	Line curvature	1.6–2.2	4–5	Pollack (in Miller, 1956).
Taste	Salt concentrations	1.9	4	Beebe-Center et al. (1955).
Audition	Intensity	2.3	5	Garner (1953).
	Pitch	2.5	7	Pollack (1952, 1953).
Vibration (on chest)	Intensity	2.0	4	Geldard (in Miller, 1956).
	Duration	2.3	5	Geldard (in Miller, 1956).
	Location	2.8	7	Geldard (in Miller, 1956).
Electrical shock (skin).	Intensity	1.7	3	Hawker (1960).
	Durations	1.8	3	Hawker & Warn (1961).

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A-16. TASK CONDITIONS AFFECTING SIGNAL DETECTABILITY DURING PROLONGED VIGILANCE
(From Van Cott and Kinkade, 1972)

Improved probability of detection		
Simultaneous presentation of signals to dual channels		Buckner & McGrath (1963), Gruber (1964).
Men monitoring display in pairs; members of pairs permitted to speak with one another; 10 minutes rest each 30 minutes of work; random schedule inspection by supervisor.		Bergum & Lehr (1962).
Introduction of artificial signals during vigilance period to which a response is required.		Garvey, Taylor & Newlin (1959), Faulkner (1962).
Introduction of knowledge of results of artificial signals		Baker (1960).
Artificial signals identical to real signals		Wilkinson (1964).
Decreased probability of correct detections		
Introduction of artificial signals for which a response is not required.		Colquhoun (1961).
Excessive or impoverished task load on operator		Poulton (1960).
Introduction of a secondary display monitoring task		Jerison (1963), O'Hanlon & Schmidt (1964), Ware, Baker & Sheldon (1964), Wiener (1964).
Operator reports only signals of which he is sure		Broadbent & Gregory (1963).
Change in probability of detection with time		
A short pretest period followed by infrequently appearing signals during vigilance.	High initial probability of detection, falling off rapidly.	Colquhuon & Baddeley (1964).
Few pretest signals before vigilance period.	Reduces decrement in probability of detection with time.	Colquhuon & Baddeley (1964).
Prolonged continuous vigilance	Decreases probability of correct signal detection.	Mackworth & Taylor (1963).

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A-17. RELATIVE DISCRIMINATION OF PHYSICAL INTENSITIES
(After Mowbray and Gebhard, 1958)

Sensation	Number discriminable
Brightness	570 discriminable intensities, white light.
Loudness	325 discriminable intensities, 2,000 Hz.
Vibration	15 discriminable amplitudes in chest region using broad contact vibrator with 0.05-0.5 mm amplitude limits.

A-18. RELATIVE DISCRIMINATION OF FREQUENCY
(After Mowbray and Gebhard, 1958)

Sensation	Number discriminable
Hues	128 discriminable hues at medium intensities.
White light	375 discriminable interruption rates between 1–45 interruptions/sec. at moderate intensities and duty cycle of 0.5.
Pure tones	1,800 discriminable tones between 20 Hz and 20,000 Hz at 60-dB loudness.
Interrupted white noise	460 discriminable interruption rates between 1–45 interruptions/sec. at moderate intensities and duty cycle of 0.5.
Mechanical vibration	180 discriminable frequencies between 1 and 320 Hz.

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A-19. FREQUENCY-SENSITIVITY RANGES OF THE SENSES
(Adapted from Mowbray and Gebhard, 1958)

Stimulus	Lower Limit	Upper Limit
Color (hue)	300 nm (300×10^{-9} m.)	800 nm.
Interrupted white light	Unlimited	50 interruptions/sec. at moderate intensities and duty cycle of 0.5.
Pure tones	20 Hz	20,000 Hz.
Mechanical vibration	Unlimited	10,000 Hz at high intensities

A-20. STIMULATION-INTENSITY RANGES OF MAN'S SENSES
(Adapted from Mowbray and Gebhard, 1958)

Sensation	Smallest detectable (threshold)	Largest tolerable or practical
Sight	10^{-6} mL.	10^{10} mL.
Hearing	2×10^{-4} dynes/cm².	$<10^{3}$ dynes/cm².
Mechanical vibration	25×10^{-5} mm average amplitude at the fingertip (Maximum sensitivity 200 Hz).	Varies with size and location of stimulator. Pain likely 40 dB above threshold.
Touch (pressure)	Fingertips, 0.04 to 1.1 erg (One erg approx. kinetic energy of 1 mg dropped 1 cm.) "Pressure," 3 gm/mm².	Unknown.
Smell	Very sensitive for some substances, e.g., 2×10^{-7} mg/m³ of vanillin.	Unknown.
Taste	Very sensitive for some substances, e.g., 4×10^{-7} molar concentration of quinine sulfate.	Unknown.
Temperature	15×10^{-5} gm-cal/cm²/sec. for 3 sec. exposure of 200 cm² skin.	22×10^{-3} gm-cal/cm²/sec. for 3 sec. exposure of 200 cm² skin.
Position and movement	0.2–0.7 deg. at 10 deg./min. for joint movement.	Unknown.
Acceleration	0.02 g for linear acceleration 0.08 g for linear deceleration 0.12 deg/sec² rotational acceleration for oculogyral illusion (apparent motion or displacement of viewed object).	5 to 8 g positive; 3 to 4 g negative. Disorientation, confusion, vertigo, blackout, or redout.

MAN'S SENSES AS INFORMATION CHANNELS

Allocation decisions must be qualified through detailed considerations of basic human capacities. Potential allocations may be rejected as incompatible with basic human capacities. The following chart is a sample of a type of data available in literature which can be used for this purpose. Allocations may be rejected or the level of human participation modified based on human demands.

In this case, an option is to supplement humans with equipment or aids to allow the operator to function within the system.

A-21. MAN'S SENSES AS INFORMATION CHANNELS: A COMPARISON OF THE INTENSITY RANGES AND INTENSITY DISCRIMINATION ABILITIES OF THE SENSES*

Sense	Intensity Range		Intensity Discrimination	
	Smallest Detectable	Largest Practical	Relative	Absolute
Vision	2.2 to 5.7×10^{-10} ergs	Roughly, the brightness of snow in the midday sun, or about 10^9 times the threshold intensity	With white light, there are about 570 discriminable intensity differences in a practical range	With white light, 3 to 5 absolutely identifiable intensities in a range of 0.1 to 50 ml.
Audition	2×10^{-4} ergs/cm^2	Roughly, the intensity of the sound produced by a jet plane with afterburner or about 10^{14} times the threshold intensity	At a frequency of 2,000 cps, there are approximately 325 discriminable intensity differences	With pure tones about 3 to 5 identifiable steps
Mechanical vibration	For a small stimulator on the fingertip, average amplitudes of 0.00025 mm can be detected	Varies with size of stimulator, portion of body stimulated and individual. Pain is usually encountered about 40 db above threshold	In the chest region a broad contact vibrator with amplitude limits between 0.05 mm and 0.5 mm provides 15 discriminable amplitudes	3 to 5 steps
Touch pressure	Varies considerably with body areas stimulated and type of stimulator. Some representative values: Ball of Thumb—0.026 erg Fingertips—0.037 to 1.090 ergs Arm—0.032 to 0.113 ergs	Pain threshold	Varies enormously for area measured, duration of stimulus contact and interval between presentation of standard and comparison stimuli	Unknown
Smell	Widely variant with type of odorous substance. Some representative values: Vanillin—2×10^{-7} mg/m^3	Largely unknown	No data available	No data available

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APPROVAL

AN APPROACH TOWARD FUNCTION ALLOCATION BETWEEN HUMANS AND MACHINES IN SPACE STATION ACTIVITIES

By Georg von Tiesenhausen

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

H. P. GIEROW
Director, Advanced Systems Office

William R Marshall
W. R. MARSHALL
Director, Program Development

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