NASA
SPACE VEHICLE
DESIGN CRITERIA
(GUIDANCE AND CONTROL)

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SPACE VEHICLE DISPLAYS DESIGN CRITERIA

MARCH 1972

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

GUIDE TO THE USE OF THIS MONOGRAPH

The purpose of this monograph is to organize and present, for effective use in design, the significant experience and knowledge accumulated in development and operational programs to date. It reviews and assesses current design practices, and from them establishes firm guidance for achieving greater consistency in design, increased reliability in the end product, and greater efficiency in the design effort. The monograph is organized into three major sections that are preceded by a brief introduction and complemented by a set of references.

The *State of the Art*, section 2, reviews and discusses the total design problem, and identifies *which* design elements are involved in successful design. It describes succinctly the current technology pertaining to these elements. When detailed information is required, the best available references are cited. This section serves as a survey of the subject that provides background material and prepares a proper technological base for the *Criteria* and *Recommended Practices.*

The *Criteria*, shown in section 3, state clearly and briefly what rule, guide, limitation, or standard must be considered for each essential design element to insure successful design. The *Criteria* can serve effectively as a checklist of rules for the project manager to use in guiding a design or in assessing its adequacy.

The *Recommended Practices*, shown in section 4, state how to satisfy each of the criteria. Whenever possible, the best procedure is described; when this cannot be done concisely, appropriate references are provided. The *Recommended Practices,* in conjunction with the *Design Criteria,* indicate how successful design may be achieved.

The design criteria monograph is not intended to be a design handbook, a set of specifications, or a design manual. It is a summary and a systematic ordering of the large and loosely organized body of existing successful design techniques and practices. Its value and its merit should be judged on how effectively it makes that material available to and useful to the designer.

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FOREWORD

NASA experience has indicated a need for uniform design criteria for space vehicles. Accordingly, criteria are being developed in the following areas of technology:

Environment

Structures

Guidance and Control

Chemical Propulsion

Individual components of this work will be issued as separate monographs as soon as they are completed. This document, "Space Vehicle Displays Design Criteria," is one such monograph. A list of all monographs in this series can be found on the last page of this document.

These monographs serve as guides in NASA design and mission planning. They are used to develop requirements for specific projects and are also cited as the applicable references in mission studies and in contracts for design and development of space vehicle systems.

This monograph was prepared under the cognizance of the NASA Headquarters Office of Advanced Research and Technology. It was reviewed and published by the Jet Propulsion Laboratory. This document was prepared under the direction of an advisory committee chaired by Dr. Jerome I. Elkind. Members of the advisory committee are listed below. Preparation of the monograph was directed by Dr. Thomas J. Triggs at Bolt Beranek and Newman, Inc.

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Contributions in the area of design and development practices were also provided by many other engineers of NASA and the aerospace community.

Comments concerning the technical content of this monograph will be welcomed by the National Aeronautics and Space Administration, Office of Advanced Research and Technology (Code RE), Washington, D.C., 20546.

March 1972

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SPACE VEHICLE DISPLAYS DESIGN CRITERIA

1. INTRODUCTION

This monograph is concerned with the guidance, navigation, and control (GNC) displays associated with manned flight.

Flight guidance, navigation, and control tasks play a central role in accomplishment of space missions. These tasks make demands on the operator which can be categorized as follows:

(1) Monitoring and decision making associated with the primary navigation and guidance process

(2) Flight control and stabilization tasks

(3) Sequencing and initializing of primary propulsion and timing systems

(4) Perceptual and pattern-recognition tasks associated with celestial navigation.

(5) Monitoring and, if necessary, operation of backup systems.

Generally speaking, the displays available to the astronaut must enable him to answer four questions:

(1) Where is the spacecraft with respect to the next flight goal or subgoal?

(2) What is and what should be the velocity vector?

(3) What is and what should be the vehicle attitude?

(4) What control actions are required to reach a desired vehicle flight state?

The types of information required fall into three main categories:

(1) Indication of state vector. Such a display, which is central to adequate flight control, indicates whether the space vehicle is in a flight configuration (position, direction, velocity) satisfactory to the next goal of the mission.

(2) Status of subsystems. Such information indicates the state of those subsystems involved in flight control.

(3) Computer-based displays. These displays may provide readout related to flight control on devices other than the more conventional flight displays.

In the U.S. manned space program, the astronaut's need to use his display system has increased in order to guarantee the proper functioning of the system as the missions have become more complex. Man's most important function is becoming more supervisory (ref. 1). For critical functions, the crew must give continual attention to several levels of backup system in order that their status be known should their use become necessary. These backup systems tend to insure functional capability but place an increased burden on the crew's attention.

The fact that the astronaut still needs adequate manual control capability has been amply demonstrated. This has been true in the Apollo as well as earlier spacecraft. In fact, the manual control demands, when needed, in the more complex system exceeded those of the earlier systems. This has been particularly so in the lunar module landing phase.

Completely automatic control has not been a design goal in manned space system design to date. Rather, the designs have been aimed at the use of human control inputs wherever they can simplify or improve the otherwise automatic operation. (For example, in navigation, the development of the sextant and the process of star tracking depended fully on human inputs.)

There has been an increasing independence of ground control as systems have developed to the stage where the astronaut is capable of completing the mission with no aid from the ground. This factor has increased the monitoring requirements placed on the astronaut by the backup systems.

Mission complexity and the allocation of tasks to human control and to automatic systems are important factors in the determination of appropriate displays. It is also important to remember that other display functions can impose demands on the astronaut which may compete with these primary displays of interest and, as such, must be considered in the design process.

Our emphasis in this monograph will be upon the methodologies useful for determining the kind of information that must be presented and how this information should be organized. This will require discussion of appropriate systems analysis techniques. Wherever possible, appropriate analytic methods for design and evaluation will be stressed. The monograph will not specifically consider implementation issues. Consideration of such factors as specific hardware details, reliability, and weight is regarded as being outside the scope of this document, except as they relate directly to the information transmission qualities of the display.

2. STATE OF THE ART

The state of the art is established from actual flight and design experience obtained in the NASA Mercury, Gemini, and Apollo programs. Experience from modern aircraft made a significant contribution as a point of departure for the initial designs of spacecraft displays. Modern aircraft technology has also led to the development of displays that are more advanced than any incorporated in spacecraft so far. In future space vehicles, this advanced aircraft technology should be incorporated in vehicle designs.

The following discussion presents the interesting features of the displays of the three NASA manned spacecraft and appraises the methodologies used in their design and evaluation. A general estimate of the display requirements for a range of missions in space flight is contained in reference 2.

Some general observations can be made of how man's interaction with displays has developed. Apparently, man's most important role will continue to move towards that of a monitor of both primary and backup systems. By monitoring, it is meant that the man is not actively interacting with the system, but checks the state of the system, using the displays to evaluate whether a desirable situation is being maintained. However, particularly in more recent experience, it has been shown that with the system to date the astronaut is frequently called upon to play a very active direct role in system control. There is a continued requirement for manual-control capability because during emergencies the man is called upon to control the system directly. The monitoring of extensive backup systems, which are provided to insure system reliability, can require maintenance or continual attention by the astronaut, which add considerably to his task load.

2.1 Mercury Space Vehicle Displays

Reference 3 provides a general description of the design of the displays for the three spacecraft systems. In figure 1, the Mercury spacecraft main display panel is shown and the principal GNC displays are outlined. This first manned spacecraft used displays similar to, but less complex than, those then used in advanced aircraft. Actual aircraft instruments were used with some simplification and miniaturization. Some of the design techniques emerged out of earlier work performed on the Dynasoar project. The critical display issue in Mercury was the need for adequate presentation of information to the astronaut during retrofire.

The Mercury spacecraft had no independent gyro horizon or flight director system; instead, the constraints of power availability and reliability resulted in attitude data being displayed on three galvanometers indicating separately roll, pitch, and yaw, with three additional needles providing information on the three attitude rates. This attitude display was of prime importance to the success of the mission, and considerable attention was devoted to its design. The final design departed from standard aircraft practice in that it displayed information coded in "fly-from" form rather than "fly-to."

By "fly-from," we refer to the situation where the moving element of a display indicates the departure *from* the required position, rather than indicating the position *to* which the vehicle is to be oriented. Considerable discussion has been devoted over the last 20 years to the most desirable procedure for coding orientation information. Although the Mercury system was a departure from normal aircraft practice, it was a successful design and yielded desired performance. The attitude control task was simplified by using a "quickening" technique (discussed later) where the attitude position and attitude rate pointers were so positioned on the display that the optimal control procedure was to keep the pointers aligned. The panel was organized according to function. On the center panel with the attitude display was an altimeter and a rate-of-descent indicator. The altimeter also represented a departure from current practice in that it was a single pointer display with a logarithmic scale. Environmental and other subsystems were separated from flight displays and were mounted on the right-hand panel.

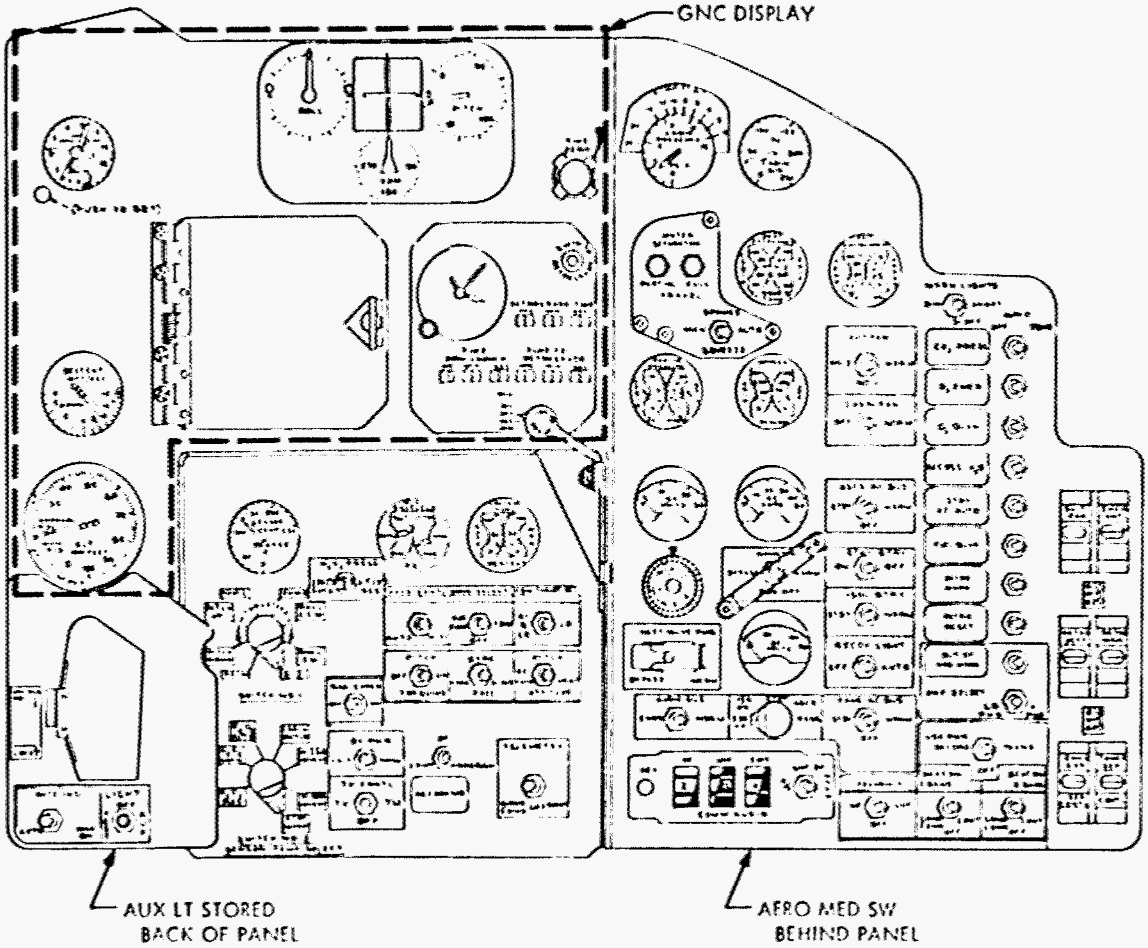

Figure 1.--Mercury spacecraft main display panel.

A workload analysis was carried out on the Mercury system, using time-line analysis which was mainly performed by hand, without computer simulation. Because the mission was a restricted one, the postulation of possible failures during the various stages of flight was a manageable problem. For a detailed description of the types of analyses performed, see reference 4. Actual performance evaluation was carried out in the simulator, where the operational situation was degraded by subjecting the displays to "blanking" at regular intervals (ref. 5).

The most demanding task that would be carried out by the astronaut was the need to counteract a perturbing torque during retrofire in manual control mode. The analysis showed that the handling of the three-axis retrograde problem required nearly 100 percent effort from the astronaut for a maximum time of 30 s. Since this task was the most difficult, it was used as the determining factor in the design of the attitude display. It was found that attitude display and use of attitude rate information were much more important here than the display and use of the actual attitude angles.

Control stick design and location were also carefully considered for the Mercury project. One line of thought suggested that the best control-display compatibility relationship would be achieved if the control stick were aligned to correspond with the axes of the spacecraft. The second approach, which was followed, was to maintain maximum similarity to the conventional aircraft cockpit. The astronauts were all skilled pilots, and it was considered desirable to maximize the transfer of habits from the cockpit to the space cabin. As a result, the attitude control was oriented as in a conventional aircraft cockpit.

2.2 Gemini Space Vehicle Displays

Although the Mercury attitude display system was different from standard aircraft displays with regard to quickening and "inside out," the Gemini system tended toward standard aircraft practice. Gemini incorporated a Flight Director Attitude Indicator (FDAI) like an aircraft gyro horizon and included the standard three-pointer altimeter.

The display panel design was much more complex than that found in the Mercury system, as can be seen in figure 2, where the principal GNC displays of the command astronaut are outlined. The Gemini's requirement for rendezvous and docking maneuver in space meant that much more information had to be provided the astronauts and that some nonaircraft displays had to be included. Workload analysis showed that the rendezvous procedures constituted the most critical task demand of the mission. Incremental velocity indicators were added to show ΔV values in all three axes. In addition, there was some duplication of basic mission instrumentation, such as an FDAI for both astronauts' panels. This added increased reliability and ease of use.

In Gemini, the first manned spacecraft to have a digital computer on board, a computer display and keyset were contained in the second astronaut's panel. Duplicate primary flight instrumentations were located in front of each astronaut, but there was no duplication of subsystem displays: these were located between the two astronauts so that either could have access to them.

2.3 Apollo Space Vehicle Displays

By far the most sophisticated manned space vehicle to fly to date has been the Apollo. This sophistication is reflected in its display system illustrated in figures 3, 4, and 5. Prior to Apollo, manned spacecraft had all the displays located within a continuous panel area. In the Apollo command module, the main display console (shown in figure 3, with the main control displays outlined) and the guidance-navigation display panels (figure 4) are located separately. In figure 5, the principal control displays are outlined for the lunar module. The Apollo main display console (fig. 3) contains flight-control, engine, communications, computer, and other subsystem displays. A map and data viewer was considered for navigation but ultimately was ruled not to be necessary for the mission. The guidance and navigation panel, the scanning telescope, and the sextant allow the celestial position to be measured automatically. The display and the keyboard assembly (DSKY) for the Apollo guidance computer are located in both the main display console and the navigation display panel, and provide a significant opportunity for mutual interaction of astronaut-controlled and computer-controlled systems. The DSKY played an important role in

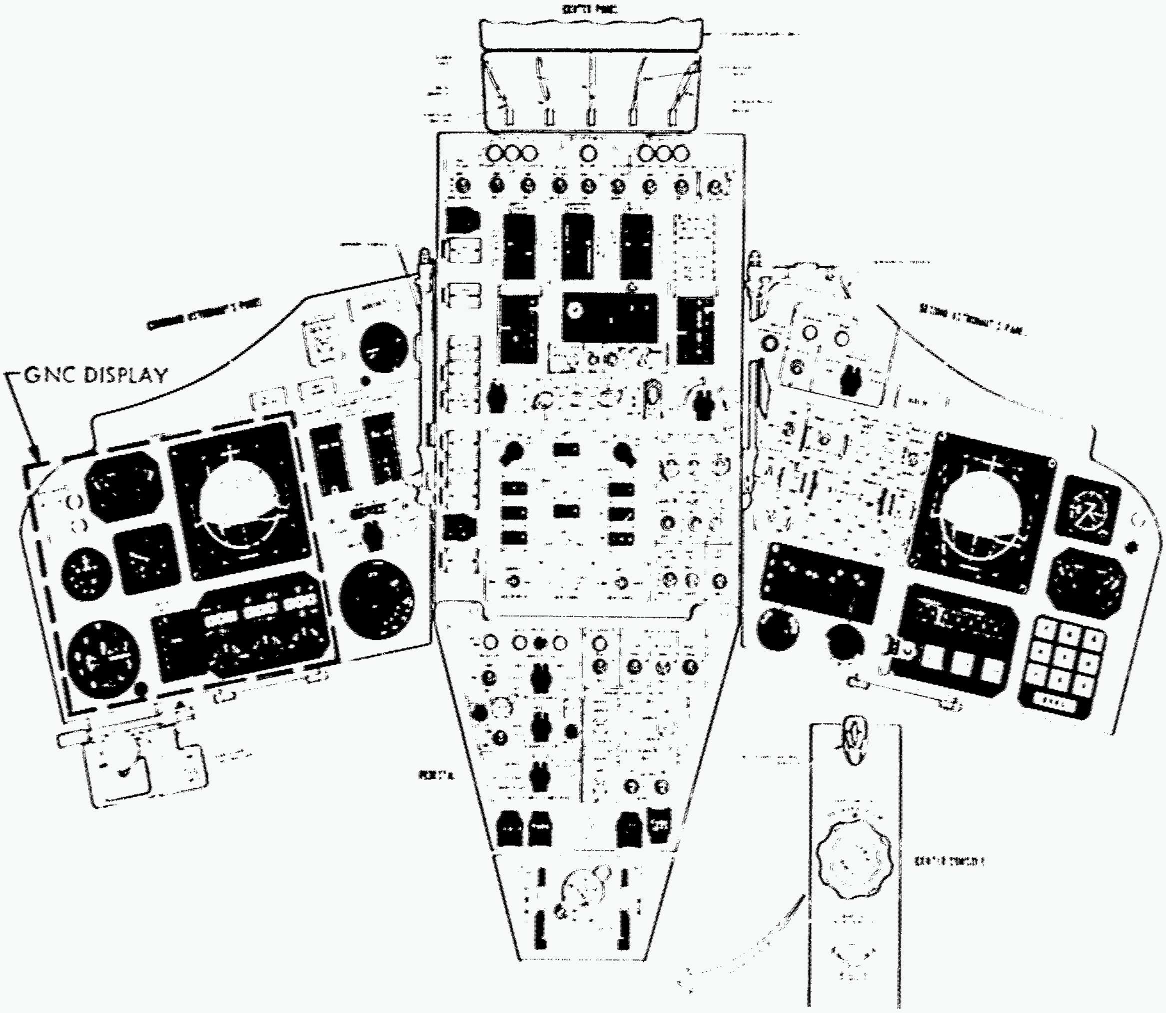

Figure 2.—Detail of Gemini spacecraft main display and control panel.

flight control in several phases of the flight and constituted the most important advancement in the display-control area over previous systems. The command module contained two FDAI, which were more sophisticated in design than the one used in Gemini. This newer FDAI, which also included display of attitude rates, was designed so that fuel use during maneuvers could be minimized.

A great deal of deliberation preceded the decision to observe current aircraft practice and utilize "fly-to" or "inside-out" displays. After initial reservation (possibly due to lack of familiarity with the display), astronaut acceptance was finally high for this display. The Apollo Command Module utilized a "g-trace display" for re-entry.

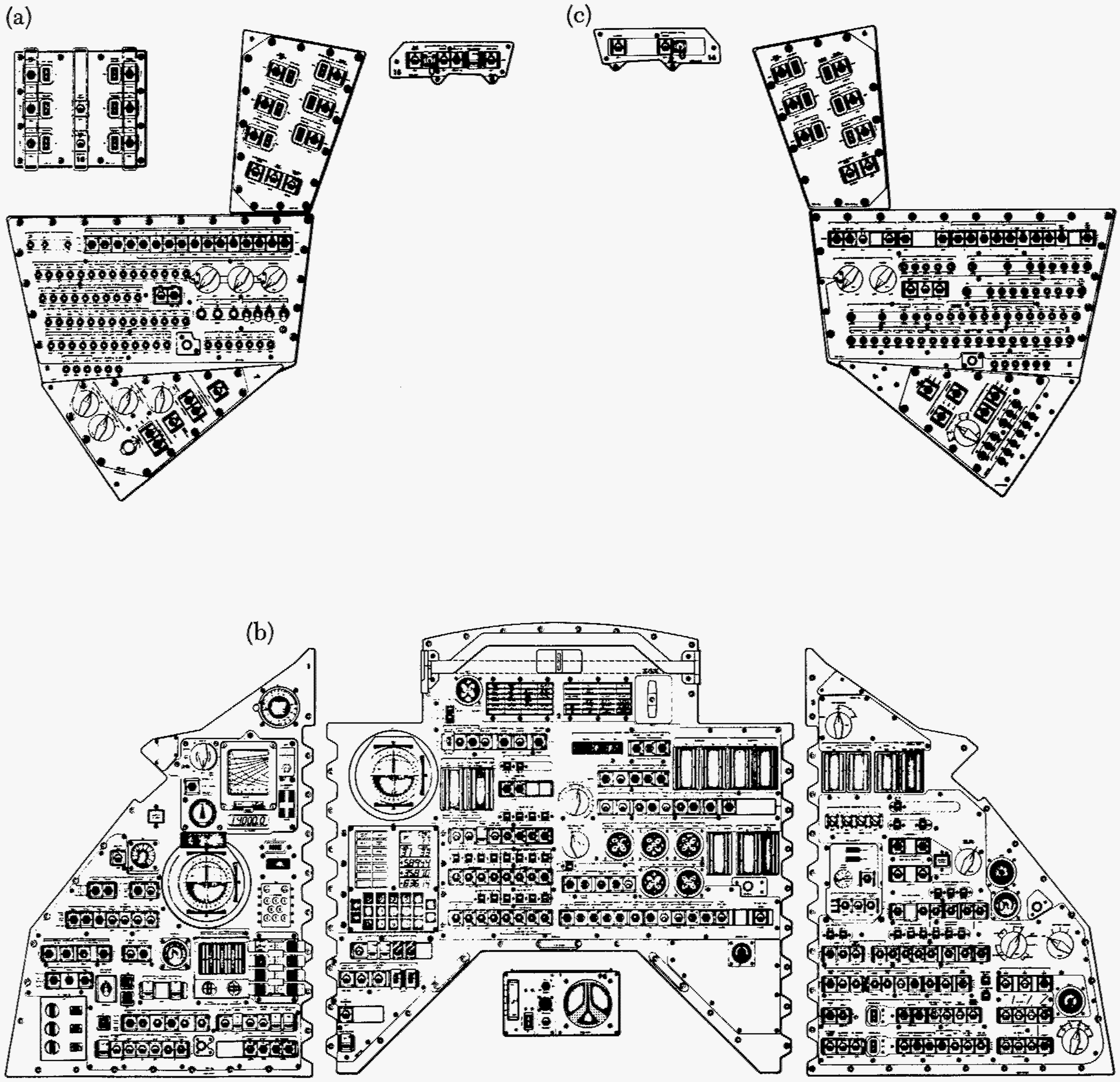

Figure 3.–Apollo spacecraft main display console (Command Module): (a) left display panel; (b) center display panel; and (c) right display panel

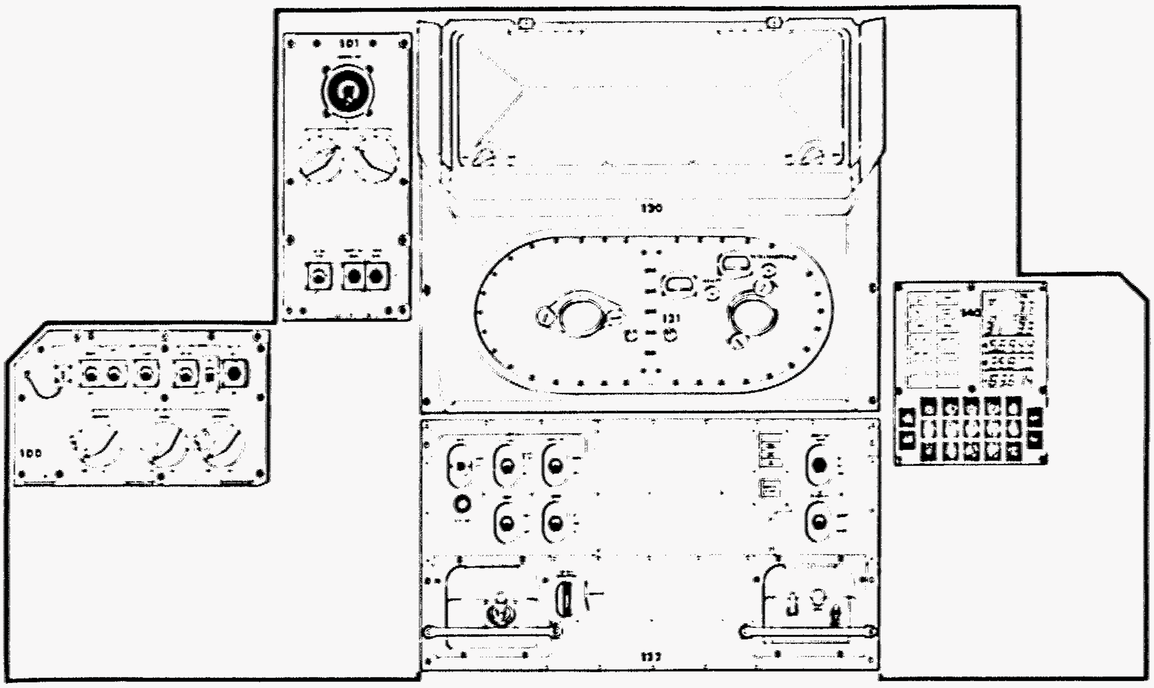

Figure 4.—Apollo spacecraft guidance and navigation panel (Command Module).

In the lunar module for the Apollo system, the two-man craft contains considerable redundancy of flight control displays (see figure 5). Each astronaut in the lunar module is provided with a gyro horizon and fore-and-aft and right-left velocity indicators. The gyro horizon was slightly different in design from that used in the command module FDAI to suit the particular requirements of the lunar landing. It was intended that interaction would occur between the astronaut and the computer via the DSKY and the translation control stick during the lunar-landing phase. The computer provides active closed loop control of the attitude and velocity vector while also accepting the desired changes from the astronaut.

In the design of operational procedures, sequences of events were organized so that the crew could maintain virtually complete control of each part of the sequence, or, where the on-board computer system exercised automatic control, the crew could be an integral part of such automatic sequencing and could monitor and take over control if necessary.

An important reduction of crew workload was achieved by having a considerable system monitoring load maintained by ground control. This meant that it was not always necessary for the crew to maintain watch over their display system, and thus allowed the possibility of leaving the lunar module unattended while both crewmen carried out exploration of the Moon on foot. Despite this ground monitoring capability, one rule established early in the Apollo development

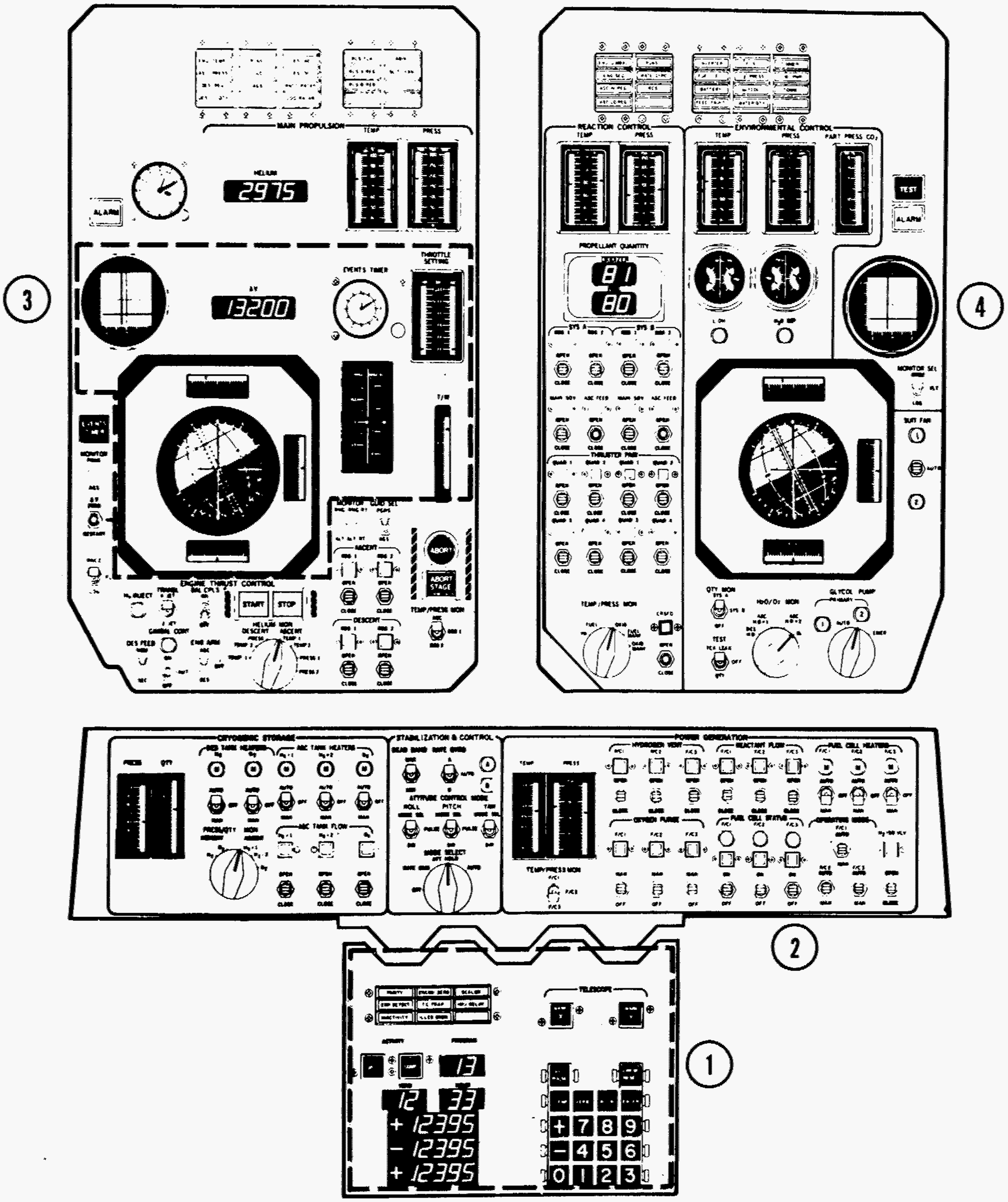

Figure 5.–Detail of panels in the Apollo Lunar Module: (1) primary guidance and navigation panel; (2) cryogenic storage panel, stabilization and control panel, and power generation panel; (3) commander's center panel; and (4) systems engineer's center panel.

was that it should be possible to complete the mission with no aid from ground control. This meant that the display systems had to be able to supply all needed information. Another ground rule that affected development of the display system was that a solitary crew member should be able to perform all the functions required to return safely to earth from any point in the mission.

Many different modes of flight control were developed to cope with various emergency situations. For example, in the Apollo attitude control system, nine different modes were developed. Each of these modes represented a different level of man-machine interaction; that is, the amounts of information processing required differed for display using manual control and for display using automatic computer control.

The Apollo display system, despite the ability of the craft to maneuver in space relatively independently of communication with the ground, was not required to display multiformatted pictorial-type sensor displays. In fact, on-board navigation data came only from three sensors in addition to inertial guidance. The navigation sensor data came only from visible optics and VHF radio range in the command module, and from radar (for altimetry, rendezvous range, and angle tracking) in the lunar module.

2.4 Important Developments From Advanced Aircraft Systems

Much of the modern aircraft display technology that has developed over the last decade has not been included in any of the manned spacecraft. For example, in aircraft, the cathode ray tube (CRT) is being used increasingly, particularly in military aircraft. However, power limitations and the need for very high reliability led to the decision not to use such devices in advanced spacecraft. There have been several important developments that will have implications for future spacecraft displays: pictorial, CRT, and head-up displays.

The most recent developments in modern displays have been made in pictorial presentation. Contact analog, head-up, and helmet-mounted displays are examples. (By pictorial is meant that type of display which presents a spatial analog of the real world and the relationship of the vehicle to its environment.) In the past, these displays have been static, in the form of printed maps or graphic road sign displays, but in aircraft, pictorial displays are most useful where they are dynamic, where the display is a substitute for a direct view of moving system elements wi.hin the operational environment. A visual pictorial display usually results from the mapping of relevant selected aspects of the reference space to the display space by a simple transform. This transform is usually veridical, in that it preserves most of the spatial and temporal relationships between system elements.

In providing such mapping, various degrees of realism are achieved. A full-color photograph is a nearly veridical display, whereas a map is more of an abstraction. Frequently, a pictorial display can provide more information than is used for normal operations, with the additional information available as needed. This allows flexibility in manned operation, which is difficult to achieve with symbolic or numerical displays.

Another desirable characteristic of pictorial displays is their capacity to display a number of variables simultaneously in a coherent frame of reference. Displays with this property enhance the ability of the operator to detect a failure in an automatic system by presenting him with an integrated, well coded means of monitoring system performance.

Experimental evidence has usually indicated the superiority of pictorial displays over conventional displays for flight control functions (refs. 6 and 7), probably because information is presented in a way consonant with normal perceptual experience and in highly redundant form. Both characteristics tend to allow rapid interpretation and to suppress erroneous interpretation.

For aircraft, two types of pictorial displays have developed (ref. 6): flight control displays (vertical situation displays), and navigation displays (plan position indicator, map or horizontal situation displays). A map display presents information concerning the ultimate goals of flight (such as destination) and is suitable for establishing subgoals (such as desired heading, altitude and speed). Backed by a suitable guidance system, a map display also allows maintenance of continuous geographic orientation. Its potential for application in space is supported by the fact that the Russian manned spacecraft Vostok had such a device.

Another dramatic change that occurred in the development of pictorial displays over the last decade was the acceptance of the CRT as an on-board aircraft display device. A CRT was first used for flight control in the A6 aircraft, and since that time it has been widely used in military aircraft. References 8 and 9 provide appropriate material on this topic.

The developing use of the CRT has resulted from the increased use of remote image-forming sensors such as radar, infrared, television (including low-light-level TV), and laser. Many missions require the display of several different types of sensor data. The outputs of several sensors, each with a different format and frame rate, are usually displayed on a single time-shared display. Time-shared displays are required because the limited usable space for sensor displays in tactical aircraft cockpits generally does not allow for separate displays. In addition to sensor information, computer-driven symbology for aircraft steering is often simultaneously presented. A number of alternative display devices have developed, such as Direct View Storage Tubes, Multi-mode Tonotron converters, and Scan converters, all of which use TV presentation to the human operator (ref. 10). Device selection depends on the specific operational environment.

Various systems of three-dimensional displays have been developed, both stereoscopic and volumetric. However, such displays do not offer enough advantage at present to compensate for the additional complexity and related problems.

Recently, there has been an increased emphasis on maintaining visual attention outside the cockpit. Although most integrated displays contribute to a reduction of the "within-panel" scanning load, other related flight display problems have been experienced. There has been a growing recognition of the need for the pilot to maintain his gaze continuously out of the cockpit at the flight path ahead, particularly on takeoff and approach to landing and under marginal visibility conditions. (Obviously, the necessity for dividing attention between the instrument panel and the external world reduces the amount of attention available for external scanning.) Although the time required to re-accommodate from outside the cockpit to the instrument panel, read an instrument, and then return to viewing the external scene will vary with the situation, one experimental estimate was 2.5 seconds (ref. 11). This transitioning constitutes a significant loss in the time available to the pilot for processing visual information.

One solution to this problem is the "head-up" display. Such displays project needed flight parameter information onto the pilot's windshield so that he can maintain attention on the flight path ahead and have flight display information immediately available. The projected display is collimated to allow the pilot to maintain visual focus at infinity. Considerable development has been devoted to this type of display. An alternative form of this development is the helmet-mounted display utilizing a small CRT and appropriate optical system. With such displays information can be presented to the pilot continuously no matter what the orientation of his head relative to the axes of the aircraft. Having achieved relatively high brightness levels and low weight, these displays appear to be a feasible alternative. Such a display also provides a simple means of displaying added information to the pilot where it is not possible to fit an added display to the instrument panel.

2.5 Display Principles

A considerable amount of handbook data on the specifics of display design has been developed since the late 1940s, particularly for symbolic displays. Such detailed design information is contained in several texts and handbooks. A good general reference is the *Human Engineering Guide to Equipment Design* (ref. 12). These handbooks supply information about what constitutes good design practice for displays that must provide quantitative, qualitative, and check readings.

Of more interest, however, to the designer of flight control displays are the more general design principles that have evolved through design and operational experience. These relate to logical rules for grouping related information into integrated displays, as well as to principles for encoding information for ease of interpretation and control. A similar set of principles is discussed in detail in reference 13; the principles and their underlying significance are briefly described below.

2.5.1 Task Hierarchy

The tasks that a pilot performs can be hierarchically organized. An aircraft pilot can exert control at a number of levels. He can control just one parameter of flight or operate at a higher level and control several parameters simultaneously. Higher-level tasks usually comprise a series of more specific, lower-level tasks. This fact makes possible the logical grouping of information into a relatively small number of integrated displays or into a small number of groups of displays. If possible, hierarchically related information should be presented in a common frame of reference or coordinate system.

2.5.2 Display Integration

In an integrated display, a number of related information items are combined and presented in a common reference system that allows the relationship between items to be perceived directly. Simply combining information items into a single display without a common reference unit does not result in an integrated display. Map displays in aircraft are one of the best operational examples of integrated displays: they yield superior flight-path control compared with the performance obtained using the standard non-integrated navigation displays. How far this integration process should be carried represents a major problem. Some flight parameters, for instance, must be present in accurate quantitative terms for stable operation, and it is not always reasonable to make such a presentation within an integrated display. Separate long-scale symbolic or digital readout displays are thus required; although it may be necessary to separate them from the integrated displays.

2.5.3 Pictorial Realism

The information content of a display should be encoded so that the symbols can be readily associated with the information items that they represent. The spatial relationships among the symbols on the display should be undistorted analogs of those in the physical world that the display represents. For instance, altimeters having vertical scales that are pictorially realistic—in that *up* means *up* and *down* means *down* in terms of the aircraft's position and motion in space—are superior for check reading to circular displays, which represent a spatial distortion (ref. 14).

2.5.4 Coordinate Systems

The element that the operator perceives as moving in a display should correspond to the element that is moving in the real world. Over the years, the most controversial issue in flight display design has been the question of what moves—the airplane or the outside world. In an analysis of pilot errors (ref. 15), a high incidence of errors resulted from reversal of instrument sensing, particularly with the attitude display.

Either of two basic coordinate systems may be used in a display. Spatial flight information may be displayed in *Earth coordinates* or *aircraft coordinates.* Earth coordinates refer to those that are fixed relative to Earth (for aircraft) and are frequently referred to as "outside-in" or "fly-from" designs. Aircraft coordinates which can be called "inside-out" or "fly-to" systems, give a representation that corresponds to the view that the pilot obtains from looking through his windshield at the Earth.

However spatial information is presented, the most critical feature of the display is the need to convince the human that the vehicle in which he is located is actually moving in space. When the outside world is perceived as moving, the pilot becomes disoriented and is subject to vertigo.

Such a false perception can sometimes occur with displays based upon aircraft coordinates. If detail is added to the aircraft coordinate display to make it pictorially more realistic, this problem of vertigo can often be reduced.

In general, since visual displays transmit information in large part by motions of elements within the display, a consistent and natural set of movement relationships must be chosen in order to obtain optimal performance from the human. This is a central problem in the design of visual displays. To have a conflict between the movement relationships has been found to cause a degradation in performance (ref. 16). In fact, it appears that it is better to have a consistent set of unnatural movement relationships than a combination of natural and unnatural movements.

2.5.5 Scaling

The scale factor chosen for a display should show as much of the total situation as possible while still being sensitive enough to allow the required precision of control. Selection of an optimum scale factor requires studying a series of tradeoffs. In general, there is an optimum scale factor for performance. As the scale factor is increased, precision of control improves up to some point at which the indicator movements exceed the dynamic range of the display, and then performance degrades. A performance cost may be involved in achieving added precision: as the scale factor is increased, the human operator often works harder on the control task and does this at the expense of attention to other tasks (ref. 17). Thus, improving performance by increasing gain on one display may lead to degraded performance on other tasks. Appropriate scale factors, then, should be determined by (1) the level of accuracy that is required in controlling the displayed flight parameters and (2) the indicator movements that will result.

In displays that include rotation of a pointer on a circular scale, certain pointer positions are ambiguous because the direction of increase can be interpreted in either rectilinear coordinates or polar coordinates (e.g., 9 o'clock pointer position is superior to 3 o'clock or 6 o'clock positions).

2.5.6 Control Task Simplification

Research on manual control of high-order systems has provided techniques that lead to a reduction in the difficulty of the task for the pilot. Many of these procedures are based on displaying additional vehicle state variables to the pilot or on combining these state variables into a command indication to the pilot.

"Quickening" is an example of the latter technique. A linear sum of state variables, usually simple derivative terms, is formed and displayed so that the operator does not have to sense and utilize derivative information separately (ref. 18). The displayed quantity constitutes a command, usually an error, that is to be nulled. A quickened display can also be used to facilitate instrument monitoring performance (ref. 19).

The attitude control display in the Mercury Capsule was a partially quickened display. The instrument actually used had cross pointers in the middle to indicate attitude, plus additional pointers to indicate rate of change of attitude. The astronaut could take advantage of the alignment of the attitude and attitude-rate needles to obtain a stabilized display. Other instruments have cross pointers in the middle and indicate attitude only. The current flight-director indicator aboard civil airliners constitutes another type of quickened display where deviation and the rate of change of deviation yield improved performance over the earlier cross-pointer instrument, which only indicated actual deviation from the desired flight path.

There is a possible limitation associated with quickened displays. A quickened display does not provide the operator with explicit information regarding the current condition of the system, and hence is of limited usefulness for monitoring the state of the system. Quickening does not have any appreciable advantage in systems where there is no delay or dynamic lag in the controlled element.

Modern flight director instruments provide both status information and effectively quickened command signals made up of an appropriate intermix of vehicle motion and guidance command quantities (ref. 20).

To reduce the workload on the human operator or to achieve stability, a display can be used with complex control systems to present future states of the vehicle in prediction displays (refs. 21, 22). To display such information, a fast-time model is operated repeatedly on an accelerated time scale and repetitively computes predictions of the real system's future based on an assumption about what the operator will do with his control. The predictions so generated are displayed to the human to enable him to reduce the difference between the predicted and desired output of the system.

2.6 Implications of Aircraft Display Development for Spacecraft Displays

Recent aircraft design and operational experience has shown that time-shared literal CRT-type displays are feasible. Although they may not yet be as reliable as electromechanical displays, CRT displays are dependable enough to represent an alternative to more conventional displays and to offer a superior and a more flexible means of presenting some types of display information. Further, the use of such displays can save panel and cabin space.

The flight control, guidance, and navigation process in spacecraft should benefit from the use of variable-format pictorial displays, particularly for critical maneuvers such as power descent and landing—maneuvers that require accurate control of space-vehicle attitude and approach to a goal. In aircraft, pictorial displays given by an airborne computer can facilitate flight control and navigation. Additional computing capability aboard a spacecraft would permit considerably more flexibility in the type of information that could be displayed.

The general display principles that have developed out of aircraft experience should hold, for the most part, in spacecraft flight control applications. These principles apply largely to pictorial displays. In choosing the elements in a display that should move, one can expect some differences between aircraft and spacecraft. In space flight, the *Earth reference* should not be as strongly established nor as relevant as it is in aircraft flight. Furthermore, the competition experienced on occasion by pilots between vestibular feedback and visual display indications can be expected to undergo a fundamental change because of the weightless condition experienced in space.

2.7 General Methodology of Display Evaluation

Despite the large amount of literature on display design and evaluation, a fully standardized methodology for a program of evaluation has not emerged, either in aircraft or spacecraft displays. Probable reasons for this lack of standardization are:

(1) The required vehicle guidance information and displayed information is so situation-specific that generalities have been difficult to catalog

(2) The responses to specific display indications depend on the overall situation and on the operator's task load

(3) It is difficult to determine the minimum or optimal information requirements that will be appropriate for the operational needs

(4) Extrapolation to operational conditions from the data obtained in simulator studies is always risky

(5) There is a lack of *system* effectiveness measures upon which measures of *display* effectiveness can be obtained and utilized

(6) Real display differences may be obscured by the experimental variability arising in complex simulator testing

(7) Frequently, display design is selected on the basis of several factors other than human factor requirements and formal analysis. Design of previous systems, panel space, engineering feasibility, available hardware, reliability, and user acceptance are all important.

Information requirements are generally determined by examining, in turn, the mission requirements, the system functions, the crew functions, performance criteria, and the specific data the crew members need to carry out their particular tasks. However, the content of information requirements can vary considerably when different formulations are contrasted. There seem to be differences of opinion among analysis experts (ref. 6). Actually, no set of information requirements is exhaustive as a result of analyzing the display needs, because some of the information the human operator requires is obtained through training and is never explicitly displayed to him. One may conclude that a list of information can be used only partially as a basis for deciding which information to include in displays and the best way of encoding this information. For a technique that alleviates some of these problems for flight control displays by using a systematic procedure based on control theory, see reference 23.

In evaluating display systems, simple experiments have been used inappropriately, in that they result in design judgments that might have been different if other experiments contrasting competing display designs had been carried out. Experiments are frequently essential in the process of developing a display design. However, experience has indicated that, if studies are not complex enough, negative results can be obtained that indicate no difference in error performance among competing subsystems, although actual differences in workload do exist. Another experiment using a task complexity similar to that of the actual operational situation may have yielded statistically significant differences between the displays considered (ref. 24).

Essentially, the problem is one of increasing the sensitivity of measures of the operator's performance (such as his error rate, workload, and reliability), so that the probability of accepting the experimental result of "no differences" is reduced. There is a real need to improve experimental sensitivity to a level capable of demonstrating even small differences between competing subsystems. When an operator is concerned only with a simple subsystem, adequate performance may be obtained. However, in the complex situation of the operational system, particularly under emergency conditions, any deficiencies in a display could be important. This puts a premium on the selection of the best subsystems.

Experience also shows that personnel selection procedures or extensive training do not seem to compensate completely for an inferior system under the degrading effects of stress (ref. 25). This further supports the need for control display analysis prior to selecting the appropriate experimental complexity when evaluating displays.

Previous experience in evaluating displays has also indicated how much the experimental results depend on the method of testing. Experimental performance measures sometimes do not reflect the appropriate psychological dimension. A study can yield statistically significant differences between the quality of the displays being compared, but the scores may not be valid indicators for deciding between competing approaches (ref. 26). The limitation of performance measures taken out of context and not relevant to operational situations is important to take into account.

In this respect, carrying out a series of evaluation tests has been shown to be appropriate: reliance should not be placed on a single level of evaluation. In fact, a hierarchy of tests and a variety of measures designed to evaluate different display aspects may be appropriate, such as preliminary screening, static open-loop tests, dynamic open-loop tests on single displays, dynamic tests in simulators, and dynamic flight tests, where each is applied systematically at different stages of system development. Examples in the literature (for example, ref. 27) have shown the importance of inter-task compatibility: how well can performance on the various displays be combined, and how do the different demands interface under concurrent performance conditions?

In laboratory evaluation of displays, information-extraction measures are those most usually obtained by the experimenter. For example, performance scores dealing with speed and accuracy of reading (legibility) or tracking error are those most frequently used in evaluation. Although these scores have good *face validity* in that they reflect how efficiently the display transmits information to the human, this type of procedure has been criticized in that it does not take account of the more complex decisions that the human must make in using information from the display. A different type of laboratory criterion (ref. 28) that has been used as a test for display effectiveness takes into account decision quality, or how well the operator can use the displayed information. Experimenters using simulations of complex-decision situations have shown that little relationship exists between traditional measures of information extraction and the measures of decision effectiveness—which indicates the possible importance of this added dimension in display evaluation. Decision quality apparently depends heavily on how the information is coded and its compatibility with the type of output required.

Performance requirements for additional tasks have made necessary other types of scores. These have proved to be additional and alternative measures to the usual display-information extraction scores (refs. 29, 30, and 31). As well as inducing increases in sensitivity in the original performance measures, the additional task can also provide additional criterion measures that can improve experimental sensitivity and/or provide other bases for system selection such as workload or learning rate. Reference 32 describes an adaptive technique that causes primary task performance to remain steady while the differences between the primary task conditions are reflected in the secondary task measures. For example, one additional criterion can be "absence of mental effort," as indicated by the ability to perform other tasks simultaneously.

Usually the rank order of competing displays is unchanged by evaluation in the presence of task-induced stress. However, the literature indicates the possibility of reversals in ordering between the stressed and unstressed conditions. This possibility is an additional justification for display evaluation under complex stressed conditions.

A further (but related) procedure for evaluating displays is to obtain estimates of the workload imposed on the operator by the task of utilizing the display system. Workload estimates have been obtained in a number of different ways (performance on an additional task, eye-movement records, time-line analysis, and the use of simulation models). Physiological measures have also been used to obtain estimates of workload (refs. 30 and 33).

Apart from experimental evaluation, attention has been devoted to developing procedures for initial evaluation of displays without experimentation (ref. 34). The Display Evaluation Index (DEI) is the most elaborate effort of this type and is intended primarily for the comparison of alternative designs. An index is computed on the basis of inputs from a number of factors reflecting principles of display efficiency. While validation study results have been favorable, the technique is not widely used.

Qualified expert opinion may also yield useful valid evaluation data. In a less structured way, panels of judges have been found to yield estimates which can have considerable validity and consistency. These estimates can be obtained at a relatively modest cost (ref. 35). User-opinion data should also be considered in evaluating a display.

There may be important advantages in simulator evaluation: simulators have considerable validity because they impose a realistic task load on the human and have a physical layout similar to the real system. They also approximate the information requirements of the system and the system procedures and frequently provide a more controlled evaluation environment than the actual system.

The level of simulation needed, of course, is determined by the goals of simulation. For example, in training, psychological realism has been shown to be important only up to some level beyond which little is to be gained. When used for the evaluation of displays, psychological realism may be relatively less important than the need for realism in physical dynamics when measuring human response characteristics under various types of stress. It is known that under stress the performance strategy regresses to a simpler mode of responding (ref. 36).

2.8 Methodology Used in Spacecraft Display Evaluation

In all three spacecraft, workload estimates using time-line analyses were performed on the whole system. The term "time-line analyses" refers to the technique of task analysis where charts are developed by plotting sequentially each task element and its time of occurrence. The series of tasks is dictated by the mission analysis and the information requirements. These diagrams then portray in fine detail the subtasks imposed on the operator as specified by observable events. Such diagrams show how the taskload on the operator varies over time.

Most of such workload analysis was performed on the Mercury system using hand analysis (ref. 4) as well as some computer simulation, but with later spacecraft the analysis was more extensive, involving very detailed computer simulation. With all three spacecraft, analyses were performed postulating large ranges of possible system failures and contingencies, and the consequent patterns of astronaut activity were analyzed for possible work overload situations. Workload estimates were made for all stages of flight, considering many possible degraded system modes. These estimates of man–machine capability played important roles in the design process, in that they permitted estimates to be made of man–machine capability prior to full task simulation (refs. 37 and 38; see also ref. 39 for a general article on these types of techniques). Estimates of workload were not taken to represent exactly that which would be experienced during actual flight, but rather the estimates allowed *a priori* comparison of various display configurations with one another by an internally consistent method, taking the range of astronaut subtasks into account.

Workload estimates from the time-line diagrams were based on the percentage of time the astronaut was occupied in a sample interval, compared with the time available, which yielded time-varying estimates of workload as the mission proceeded. A general rule of thumb has developed in estimating what constitutes acceptable workload levels, the rationale being that high workloads lead to situations in which errors in task performance increase markedly. Experience has indicated that, during active performance by an astronaut, he should be kept 60–70 percent occupied in order to obtain the most consistent performance (ref. 40). At workloads higher than this figure, errors in task performance can be expected to increase markedly. This type of analysis showed that on the Mercury system, for example, the astronaut could be 100 percent occupied for brief periods of time, although the task loading was much less than this throughout most of the mission.

The Apollo mission requirements were frequently altered and refined as the system was being developed. This made possible a flexible approach to task analysis through the use of the computer to synthesize a time-line diagram from the series of discrete tasks and to develop a composite workload by applying a simple set of strategies to schedule tasks for minimum workload. This approach also considered task priority (by which certain tasks would take precedence over others) and task assignment by crew member. Initial allocation of tasks among the three crew members in Apollo was done informally on a relatively *ad hoc* basis. This allocation was then modified along with the information requirements and the occurrences of each task in time as dictated by the mission analysis. Various iterations were checked and the final allocation verified by the results of time-line and workload analysis.

Various human performance measures were recorded for individual tasks to serve as input parameters to these time-line (or discontinuous) analyses. Movement-time measures were taken for switch actuations and other astronaut responses where these depended on the distance moved, the direction of movement, and the type of control motion used. Interpretation time estimates, made for individual displays, depended on the nature of the display, the level of accuracy required, the range of values the display could assume, and the rate of change. Of some significance were the eye movement data obtained, which formed a basis for allocating time for scanning from one instrument to another. Eye-movement records also indicate how efficiently the astronaut can scan the displays in the various task sequences and whether other panel arrangements may be more nearly optimal. Such analyses were carried out on the X-15 aircraft display panel (ref. 41). These records also indicate whether some displays can be read satisfactorily using the visual periphery. For example, with Apollo, it was verified that on the FDAI the rate attitude needles could be read by the astronaut as he fixated the actual attitude display.

Later in the design stage, experimental evaluations of astronaut performance were checked out in whole task simulators. Essentially two types of workload estimates were made using the simulator. First, could the astronaut actually carry out the tasks required of him to the desired level of accuracy in a whole-task simulation (in a full six-degree-of-freedom simulator with realistic motion cues and a valid exterior view)? Second, did this accuracy requirement allow the astronaut a workload far enough below 100 percent to permit him to respond with a low incidence of errors and to cope with unscheduled contingencies in actual operation?

In the Mercury simulation, a "blanking" technique was used whereby the display system was put under intermittent illumination (ref. 5). This was intended to evaluate whether the astronaut could perform the taskload required of him under these degraded conditions. The effect of intermittent illumination on the multidisplay task situation had been previously calibrated (ref. 42). For the later spacecraft, a spare information-processing capacity estimate was made by requiring the astronaut subject in simulation to perform on an additional "bit-box" task. Such a procedure had been used previously with evaluation of pilot performance with the X-15 (ref. 43). This auxiliary task consisted of an array of light which required cancellation by a key-button response, and the response frequency enabled a measure to be obtained of how spare capacity varied through the mission.

Astronaut users were involved intimately at times in the design process. They contributed to the design and assessment of vehicle handling qualities, provided feedback on desirability of certain display characteristics, acted as subjects for simulation evaluation, and were involved in the design of control stick forces, lengths, and shapes.

Neither purely display human factor considerations nor workload estimations were the sole determiners of display design. For example, the selection of the Gemini three-pointer altimeter was based on its ability to match cabin dimensions. Alternative and more desirable displays, available off the shelf, did not satisfy this size criterion.

2.9 The Use of Analytical Models

2.9.1 Role of Analytical Models

Analytical models of pilot–vehicle systems may be used to provide a preliminary evaluation of competing display configurations without the necessity for complex simulators and in-flight studies. These models allow the designer to take a systems approach to several aspects of display design and development. It is possible to consider vehicle dynamics, disturbance, mission criteria, and human capabilities and to determine analytically the way in which these factors interact with the type and quality of displayed information in terms of overall system performance.

Studies of human monitoring and control behavior that have been performed to date have yielded a sizable data base from which we may infer general, quantitative relationships between model parameters and parameters of the control environment. We can, therefore, use existing pilot–vehicle models to predict system performance and pilot behavior for various control systems and display configurations not hitherto investigated. This is important, because the suitability of a given display configuration is highly specific to the nature of the control task.

2.9.2 Brief Description of the Models

Quasi-linear models of pilot–vehicle systems have been developed to a high degree, and we consider models of this type to have the greatest potential with respect to evaluation of displays. In these models, the pilot is represented by a linear response element (the pilot-describing function) plus a "remnant" term (to account for the portion of his output that cannot be accounted for by the describing function). Model parameters are most readily interpreted when the vehicle dynamics are linear and when the statistics of the control environment are time-stationary. The appropriate pilot strategy is to behave as a linear, time-stationary controller. The describing function may then be interpreted as the deterministic linearized portion of the pilot's strategy, with the remnant representing purely stochastic behavior. If instrument scanning is required, the pilot's monitoring strategy (and possibly his control strategy) will be time-varying. Quasi-linear pilot–vehicle models may be usefully applied to situations of this type as well, but measurements of pilot remnant will reflect the time-varying nature of the pilot's response strategy as well as truly "random" behavior.

Quasi-linear models fall into two basic categories: the frequency-domain representation (ref. 44) and the state-variable (or "optimal-control") model (ref. 45). Both representations allow one to predict pilot-describing functions and measures of overall system performance such as mean-squared system error. There are, however, considerable differences in the computational techniques employed by these two types of models. References 44 and 45 provide detailed descriptions of these models.

Both kinds of pilot models contain elements that may be identified with specific physiological or psychophysical functions. The frequency-domain models, for example, often include specific representations of the neuromuscular system. On the other hand, the state-variable model represents the pilot's estimation and control strategies as distinct elements.

Frequency-domain and state-variable pilot-vehicle models may both be profitably applied to the area of display evaluation. In the remainder of this section, the specific potential capabilities of these models is outlined.

2.9.3 Specific Capabilities of Analytical Models

Pilot-vehicle models have reached the stage of development at which they may be used to explore the aspects of pilot behavior and system performance described below.

(1) Total System Performance

For situations in which the vehicle dynamics can be linearized and the mission requirements represented unambiguously in a suitable mathematical form, analytical models may be used to predict overall system performance. Thus, these models can be used to determine the extent to which mission requirements can be met with a given display configuration. By noting the effects on system performance of changes in one or more display parameters, (1) determine the information requirements of the system, (2) determine improvements associated with display quickening and predictions, and (3) compare the relative merits of command information versus error information. Considerable modeling success has been obtained in this regard, and the model can now be applied with reasonable confidence to the problem of predicting overall system performance and how the performance changes with modifications to the display.

(2) Pilot Response Behavior

The input-output behavior of the pilot (i.e., the combined perceptual, central-processing, and control behavior) is predictable. The response strategy is usually presented in the form of a describing function (or set of describing functions). Comparison of predicted behavior with response strategies measured in "conventional" flight-control situations will indicate whether or not an unusual response strategy is demanded by the system under investigation. Considerable success has been obtained in predicting pilot-describing functions in a variety of control situations; hence, applications of this sort are warranted.

(3) The Pilot's Estimation Strategy

The pilot's estimation strategy can be predicted for situations in which the pilot acts as a monitor only. A model of this sort is quite valuable in predicting system transients that occur when the mode of control switches from automatic to manual.

(4) Pilot Workload

Models have been developed which appear capable of predicting scanning workload, i.e., the fraction of attention that the pilot will devote to the various displays (ref. 46). Models have been applied to systems containing physically separated displays as well as those in which a single multielement display has been used. In addition, a model has been developed to predict central-processing workload, i.e., the amount of attention that must be devoted to the task as a whole in order for mission requirements to be achieved (ref. 47).

(5) Instrument-Related "Noise"

The state-variable model contains a set of parameters associated with perceptual noise. To some extent, these parameters may be adjusted to account for the effects of random disturbances inherent in the display hardware (such as sensor and meter noise). They may also be used to represent resolution limitations of the human's visual system plus random response behavior arising from signal/noise limitations of the human brain's central processing mechanism (refs. 48 and 49).

(6) Handling Qualities

Pilot–vehicle analysis has been applied extensively to the study of vehicle handling characteristics (refs. 50, 51, 52, 53, and 54). Several approaches have been explored. Although none has achieved universal application, some general observations can be made. The pilot's rating of a vehicle's handling qualities is influenced by the nature of the open-loop response characteristics of the vehicle, by the closed-loop system performance that can be achieved in various task situations, and by the nature of the response strategy required of the pilot. It has been found, for example, that pilot ratings worsen as tracking error increases and as the lead that must be generated by the pilot increases. Some success has been achieved in modeling the relationship between pilot rating, pilot lead, and system performance. Since pilot–vehicle models are capable of representing both the informational characteristics of the display and the perceptual limitations of the human, these models should prove useful in exploring the relationship between display parameters and vehicle handling qualities.

(7) Effects of System Failure

By investigating the effects of sudden changes in the display and system parameters on pilot behavior and system performance, one can predict the ability of the pilot to recover from a failure condition. Accordingly, the suitability of the display configuration in a situation of this sort can be evaluated (ref. 55).

(8) Sensitivity to Pilot Strategy

The sensitivity of closed-loop system performance to changes in the pilot's response strategy can be predicted. For example, one can explore the effects of a constant bias in one or more of the pilot's response parameters, or one can look at the effects of an increase in the magnitude of random fluctuations in these parameters. Although this aspect of the model's predictive capability cannot readily be verified experimentally (since the pilot will usually attempt to select the appropriate response strategy with a minimum of random response activity), predictions of this sort should prove useful in the evaluation of system controllability and pilot acceptance.

3. CRITERIA

3.1 System

The display system shall provide the information needed by the astronaut to navigate and control the spacecraft within specified accuracies for all mission phases requiring him to do so. It shall be designed to permit the supervision and management of the performance of the automatic GNC systems and related backup systems. The displays should also enable the operator to adjust automatic systems.

The system should always provide some means (buttons, switches, etc.) that shows the applicable array of mission phases and control modes available, plus the one that has been selected. Digitally coded keyboard entries as a primary means of selecting major control modes and mission phases shall be avoided.

The display system should be designed so that system performance is relatively insensitive to the pilot's information-processing and control strategies.

The display system should allow the specified handling quality to be achieved.

The redundancy in the display system shall be consistent with the reliability requirements of the mission.

Wherever possible, where astronauts are involved in space flight of long duration, facilities should be provided for practice using the displays and controls that will permit the maintenance of performance efficiency.

Typical astronaut users should be consulted and participate actively in all phases of the display design process so that user requirements can be meaningfully taken into account.

3.2 Emergency Performance

Information shall be presented to aid the detection of and the recovery from failures in the GNC system. The display system design should be such that manual takeover from automatic control can be accomplished with acceptable transients. Displays of emergency conditions should be designed to permit information interpretation to be as rapid as is necessary to make possible a timely response.

Where practical, automatic controls should be designed to perform maneuvers in the same way as the pilot, using the same displays. This will minimize takeover transit if takeover is required.

Displays should fail in such a manner that no false display of information occurs during the failure process of any part of the system. The failed display should indicate its inoperative status clearly and unambiguously.

Controls should be designed so that the relationships between all control-display movements are the "natural" or "expected" ones and no unnecessary mental process is required between comprehension and response, so that control reversals will not occur during emergencies or in stressful situations.

The display design should take into account the degradation of human performance which would result from the astronaut's being subjected to environmental stress such as vibration, high acceleration forces, hypoxia, etc.

3.3 Display Integration

Display should be such that the smallest number of crew members can perform all control and monitoring functions necessary to accomplish a safe return from any point in the mission.

Control mode displays must always show what mode of guidance and control is being used even when some sort of switching and sequencing is performed under computer control. Momentary indications are not adequate.

System integration factors such as power, weight, and size should be included in consideration of appropriate display designs and selection.

Critical GNC displays should be located centrally, and nonessential displays should be removed in either position or time.

Controls should be located to insure that continuous viewing of critical displays is possible. All controls and switches to be used in a critical maneuver should be located so that the astronaut does not have to move his eye far from the location of the critical displays.

Displays and controls should be organized in some logical arrangement in order to facilitate accomplishment of complex procedures, both routine and emergency.

3.4 Specific Display

The tendency of a display to yield reading errors for one particular type of indication should be guarded against (bias errors). System design should be insensitive as far as possible to the effects of minor reading errors. Interpretation time should be minimized for the higher-priority displays. The display system should be designed to minimize occurrence of either (1) undesirable vestibular responses or (2) undesirable visual phenomena, such as apparent movement effects (known generically as the Phi phenomena, in which movement in the visual field is perceived without actual physical movement of the stimuli) or the autokinetic effect (in which, in the absence of a visual frame of reference, a point of light may be perceived as moving or drifting).

Cockpit lighting and display brightness shall be such that all displays are fully legible irrespective of brightness and direction of outside ambient light entering through cabin windows. The cockpit lighting and glareshields shall be designed so that reflections off cabin windows do not hinder operations depending on visual information entering from the outside. The display illumination level should be adjustable to match the different light adaptation levels the crew will require.

3.5 Workload

The display system shall be designed so as not to add unnecessarily to the amount of workload resulting from the task demands. The display should provide the necessary information in a manner that minimizes the information gathering and processing workload of the astronaut.

The displays should present sufficient information to prevent the exceeding of human or system tolerances.

The human visual scanning workload should be minimized where real minimization does not contribute to increased display interpretation time and possible confusion between different instruments.

The performance tasks should, as far as possible, be distributed appropriately between crew members if it can be arranged without compromising performance or requiring an excessive amount of equipment. Consideration should be given to rotating duty shifts since task splitting could lead to functional weaknesses. When actively involved in system operations, each crew member on duty should have an approximately equal workload; and in emergencies, the overload imposed on any one crew member should be minimized by distributing the load to the other crew members.

Information should be presented so that the amount of processing required to arrive at an appropriate operator response should be minimized (techniques such as quickening and prediction are examples of this). Display processing rules should be as uniform as possible. Changes of rules between displays within the one panel should be eliminated if possible.

When the human operator must monitor vehicle performance under automatic control, higher-level information should be presented to permit easy understanding of the system state; the display should also contain information appropriate for manual control of vehicle.

4. RECOMMENDED PRACTICES

4.1 System Considerations

For adequate display system design to be assured, it is essential that those responsible for the system be involved early in the design process when the mission and general system concepts are being developed. Only general methods of task analysis need be used in these early stages, but they will include a systematic examination of the behavioral requirements of tasks and the implications of automating tasks compared with manual control. As system design proceeds, the task analysis is usually iterated, becoming more specific as the system proceeds from the conceptual stage to the detailed development stages. For a general description of system analysis procedures, see reference 56.

It is recommended that the baseline information requirements be determined by the following sequence of analysis steps. These steps should be performed to the level of detail necessary to ensure precise definition of the system display requirements. Each step may require several iterations before a final set of requirements is reached, and analytical models can play a role in determining the requirements. An outline of the development cycle is indicated in figure 6.

4.1.1 Mission Analysis

Mission analysis requires determining and stating as precisely as possible the purpose and goals of the system, and what will constitute the measures of system effectiveness. Details of required accuracies, reliabilities, and system performance criteria should be assembled at this stage. However, data on reliability of pilots' reading instruments is very limited and simulation is necessary to achieve even gross estimates. The mission analysis should include a statement of the environmental and time constraints accompanying mission performance. This analysis leads to a definition of requirements that are expressions of obligations the system must fulfill to carry out its mission. Requirements are usually stated first qualitatively and then become increasingly more precise as system development proceeds.

4.1.2 Development of Functional Flow Diagrams

The next step is to perform and diagram the functional analysis based on the mission; i.e., to identify the means by which elements of the mission can be accomplished, and then to relate these separate means with one another to form a diagrammatic structure of how the mission is to be accomplished, with particular emphasis on the man-machine interface. Such diagrams translate system requirements into functional terms, identify functional interfaces, and allow segmentation of the mission into smaller analysis units.

4.1.3 Information Requirements

A listing of the decisions required in the tasks allocated to the astronauts can now be made, and from this a list of information requirements can be drawn up. The list of information requirements will serve as a general indicator of the types of display that are required for specific functions and subtasks. However, the listing alone will not lead to such a display specification; many other system factors will have an influence here.

In this step, one needs to define the variables that should be displayed, the range and precision of these variables, the bandwidth the display has to cover, and the variable derivatives that need to be displayed.

4.1.4 Task Allocation

The tasks required to complete a function should then be decided upon, and these are allocated either to the human operator or to the hardware system. Those tasks requiring display inputs to

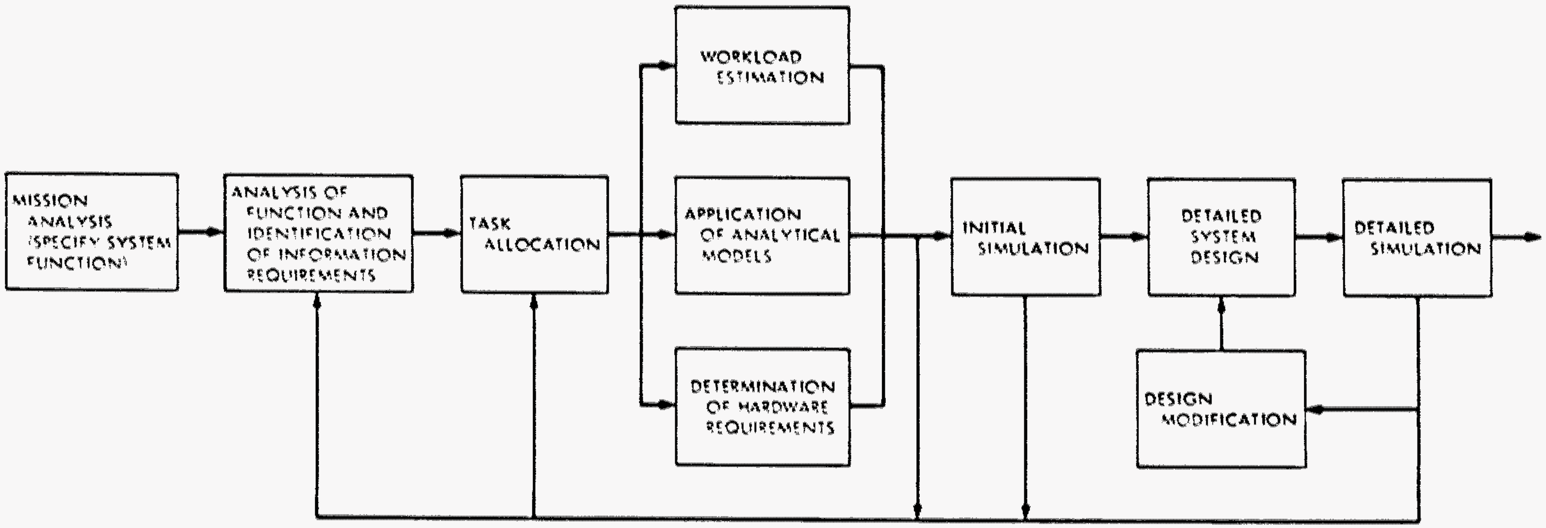

Figure 6.—Idealized development cycle.

the human can then be established. Choice of functions should reflect a combination of the following: (1) judgment and intention based on similar systems; (2) dictates or constraints of the user; and (3) critical analyses, experiments, and simulation studies involving tradeoffs of alternative configurations of automatic and manual performance, and incorporating what is known about man, machine, and man–machine performance. Assigning functions in a particular system is not helped by a set of rules determining allocation. The method of attack is an iterative one based on many specific system development considerations (ref. 57).

4.1.5 Time-Based Analysis

The feasibility of presenting the required information to the human within his information processing and responding capabilities can be tested by using time-based analysis techniques (ref. 58). This should be performed initially in a relatively gross way, but should eventually be refined and elaborated, using the types of computer-based simulation models described in reference 39.

4.1.6 Application of Analytical Models

Analytical models, including performance measures of information quality, are recommended for use if required to determine the effects on closed-loop man–vehicle systems. For example, it may be required in special cases where real-time manned simulation is not feasible or practical. In other cases, where conflicting results exist, an analytical rationale would help reconcile the differences. Specifically, it is recommended that human controller models (refs. 44 and 45) be utilized in evaluating the adequacy of the display design characteristics used to present flight control information to the astronaut. A methodological procedure for flight control display system design is offered in references 23 and 59. The effects of varying relevant display parameters will provide more information on display system requirements (prior to experiment and simulator development) and indicate the advantages of competing types of control systems.

These types of system analysis procedures should be carried out as early as possible in the systems development to provide indications of the types of displays systems that will yield the necessary levels of performance to enable successful completion of the mission. The system equipment requirements for several types of orbital missions under manual modes of control are discussed in reference 60.

4.2 Degraded-Mode Analysis

No panel display can be considered adequate unless it is subjected to a degraded-mode analysis on several levels. The loss of subsystem functioning should be considered at a number of analysis levels: (1) the change in information requirements, (2) the effects on task workload, (3) the implications for display panel layout, and (4) evaluation of the degraded effects in simulation on mission accomplishment.

4.3 Integrated Crew Performance

The performance of the integrated team of astronauts should be studied at several stages of the systems development. Earliest allocation should be on the basis of expert opinion, which should then be subjected to evaluation using simulation models such as those described in reference 39. The training required in order to perform certain groups of tasks should also be considered, and tasks should be allocated so as to minimize the training requirements.

4.4 Selection and Evaluation of Specific Displays

The preceding analysis will serve as an input into the selection and/or design of specific display devices. Added considerations should include the display principles previously discussed and handbook data (e.g., ref. 12) to insure that the actual displays are best coded. Such factors as display size, index design, size and type of numerals, and display scaling will be considered.

The adequacy and completeness of information presentation should be examined through carefully designed experimental programs. Such validation should take place on several levels ranging from consideration of the adequacy and comparison of single displays in subsystem performance to system evaluation in part- and full-task simulators. Quantitative descriptive measures such as speed and accuracy of response and error scores should be recorded and summarized in terms of means and standard deviations. Where relevant, the data will be analyzed according to established statistical procedures to evaluate the statistical reliability of the results and to discover the relative importance of the experimental variables considered. (For a general reference on this topic, see reference 61.) The experimental data will be obtained using experimental procedures which allow satisfactory analysis of the data. Careful planning will be required to cast an experiment into a form that will permit a standard design to be used or to be modified to more closely meet the requirements of the experiment. Good principles of experimental design will be applied.

Variables should not be grouped together in the experimental conditions so that their direct effect cannot be estimated (for example, in experiments with displays, the design should separate the effects of the control characteristics of the task from the quality of the displays used). Large enough samples of appropriate subjects should be used to insure the representativeness of the results, and experimental subjects should be drawn from the population of actual user types. Where several variables are to be displayed on one multipurpose display device, it should be determined that there is no ambiguity or confusion resulting from using the same device at the same location to display different information at different times.

It is recommended that experiments be conducted with the following intentions in mind: (1) to evaluate the effect of a particular display configuration compared with expected performance (the normative model); (2) to form estimates of workload; (3) to collect basic human response data to be used as baseline inputs to discontinuous computer analyses for computing workload; (4) to determine that combination of equipment parameters which would lead to satisfaction of required performance criteria.

4.5 Workload Estimates

Attention should be focused throughout systems development on the workload imposed on the astronaut. It is recommended that the following techniques be considered for use in evaluation of this workload.

Expert opinion can be relied upon very early in the development cycle from panels of both experts and users in the field of human factors. However, users may not always react favorably at first to novel display developments.

As system development concepts become more specific, peaks of workload or stages of overload should be identified by applying discontinuous analysis, time-line analyses (ref. 37), or man–machine simulation models (ref. 39). Various system configurations and procedures should be subjected to this analysis in order to evaluate competing subsystems and to perform an initial allocation of duties to the various crew members.

As equipment configurations are selected and mockups developed, application of procedures for estimating workload experimentally are recommended for verifying that the display system and procedures generally allow each crew member to maintain spare mental capacity for meeting emergencies or deviations from standard procedures. The recommended procedure is to obtain estimates of spare mental capacity by recording the astronaut's ability to perform a subsidiary task simultaneously with allocated system tasks (refs. 29 and 32). In selecting such an additional task, the following desirable properties should be remembered:

(1) It should be "wide-band," i.e., should measure spare capacity over a wide range

(2) It should yield efficient measures and be reliable over short periods of time

(3) It should require minimum learning

(4) It should be quantifiable, in terms of a suitable metric.

The visual scanning workload should be measured by recording eye-movement patterns so that the layout of instruments on the display panel can be evaluated, and changes in panel layout incorporated in the design to minimize this scanning load (refs. 41 and 46).

The following two general rules can be applied to improving panel layout (ref. 62): (1) The greater the probability that a display will be fixated, the more centrally in the visual field it should be fixated; and (2) The greater the probability of transition between two signals, the closer together they should be displayed. Methods for recording eye movements are described in references 63 and 64.

Recording visual scanning patterns of the astronaut can also shed some further light on the information requirements of the user and the strategies the astronaut is using to monitor his display system (refs. 62 and 65).

Of these methods of obtaining workload estimates, expert opinion represents the simplest and least expensive method, but is most restrictive in terms of detail and validity. The discontinuous analysis techniques can be applied prior to the actual production of mockups or simulators. It can be used to evaluate a number of different configurations, and the level of analysis detail in this technique can be altered by changing the basic time unit considered. These two procedures are more relevant to the early stages of design. The procedures of estimating spare mental capacity and visual scanning workload are more relevant to the later design stages and, applied to a full task simulation, have the highest face validity. The procedures may have to be iterated several times before a final design is selected.

4.6 Simulation

Any display development would be incomplete, particularly in complex vehicle systems, without adequate simulation evaluation. In the early phases of the program, simple, single-task simulations should be sufficient. At the later stages, simulation must be used to indicate whether the crew members are able to utilize the information from the display system to perform the mission with a high enough reliability. As the system develops, simulation should become more and more a full-task simulation. Where the astronaut is required to combine visual information from outside space with display system information, it is recommended that the simulation incorporate visual scenes from outside the cabin with good fidelity.

Experiments to determine the ability of the astronaut to detect and recover from failures using the proposed configurations are recommended. The experimental plan for these experiments should be aimed at (1) obtaining data on whether the human operator can use the displays at his disposal rapidly enough to permit recovery from the failure, and (2) after failure, whether the degraded or standby display-control system possesses adequate characteristics. These can be evaluated by workload measurement, simulator performance, and application of human response analytical models.

If there are any questions about the efficacy of the display-control relationship, these relationships should be evaluated by measuring population stereotypes for all display-control pairings, using such techniques as primitive mockups, before selecting the operational relationships. Wherever possible, uniform rules relating display and controls should be striven for. For a general review of population stereotypes, see reference 66. However, the fact that the astronaut user is highly skilled and represents a small user population means that the design can be tailored to meet his specific needs.

Visibility tests should be performed in a mockup to insure adequate display visibility under all ambient lighting conditions that can be expected during the performance of the mission.

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