EFFECTS OF HIGH G CONDITIONS ON PILOT PERFORMANCE

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The general development trend in space vehicle design suggests the desirability of maximally using the occupant to both control capsule attitude and to monitor vehicle systems during the boost (and reentry) acceleration phases, as well as during orbital flight. Consequently, much more information is needed concerning man's ability to perform certain control functions under conditions in which he is exposed to accelerations which approach not only his physiological tolerance limits, but also his performance tolerance limits. In addition to the need for more data concerning the acceleration stress that man can endure and still retain the ability to perform control functions, there is a need to know specifically the nature of performance errors which can arise, not only as the direct result of acceleration, but also as secondary effects of acceleration interacting with other conditions such as the type of control task, the type of control device, the damping and stability parameters, and the pilot's physiological endurance[8]. Current concern over the performance capabilities of the human pilot immersed in cèrtain acceleration environments is well founded since there are very few experimental reports describing the effects of these conditions on performance. The present paper attempts to summarize some of the results of recent studies conducted at the Aviation Medical Acceleration Laboratory (AMAL) in which specific pilot performance capabilities were studied under several conditions of acceleration stress.

General Experimental Method

The primary apparatus was the human centrifuge, located at AMAL, Johnsville, Pennsylvania (Figure 1). By applying suitable signal inputs to the servo systems controlling the radial velocity of the centrifuge arm and the motion and position of the two gimbals, the centrifuge provides the capability for exposing a pilot positioned in the gondola to acceleration fields which may vary along the dimensions of direction (vector), amplitude, duration, rate of onset, and complexity. Equations of motion and related vehicle characteristics, stored in a computer system, also may be programmed to present acceleration and control display conditions to the pilot as he "flies" realistic flight problems using a display panel such as that shown in Figure 2. The accelerations and displays thus received are functions of the pilot's performance interacting with the aerodynamic equations and vehicle characteristics stored in the computer. A relatively large variety of studies have been conducted utilizing this facility and general approach. Some of the studies have been concerned with basic human abilities within certain specified acceleration environments. These types of studies are to be contrasted with the vehicle simulation studies which were more oriented towards studying man's interactions with specified flight tasks and predicted vehicle conditions.

Linear acceleration is simulated on the centrifuge by using angular velocity. Three linear acceleration components may be simulated and emphasis is placed upon these. So far as the pilot is concerned, it is convenient to consider the acceleration environment in terms of the three components (Figure 3). These components are G_x (acceleration along the pilot's dorsal-ventral axis), G_y (acceleration along the pilot's side-to-side axis), and G_z (acceleration along the pilot's longitudinal body axis). Since the relative orientation of the pilot with respect to the resultant acceleration vector can be continuously controlled, any given vector may be positive, negative, or zero, depending upon the pilot's position with reference to the primary acceleration vectors. The acceleration nomenclature used in this report is the physiological-heart-displacement system[5, 16]. Regardless of whether the subject is in the seated position, the supine position, or the prone position, this nomenclature system refers to the physiological displacement of the heart within the chest when a particular acceleration force is applied. In the current report, we are concerned primarily with positive G_x (heart displaced towards the spinal column), minus G_x (heart displaced away from the spinal column), and plus G_z (heart displaced downward). Sometimes these vectors are referred to as eye-balls-in, eye-balls-out, and eye-balls-down, respectively.

To date, a consistent terminology for representing acceleration and its various components has not been adopted for úniveral use by engineering, biological, physiological, and psychological groups. There is much variation in nomenclature, even within the same laboratory. More detailed discussion of the problems of acceleration nomenclature may be found in Dixon and Patterson [18], Gauer [22], Clark, et al [16], and Chambers [5].

For this report, the G system of units proposed by Dixon and Patterson [18] is used throughout, as the measure of acceleration force, although it is recognized that there is much confusion in the field regarding this terminology. In practice, therefore, G is considered as a unit of force and observed accelerations are expressed as so many "G's". For example, terms such as "6 G units" or "a force of 6 G" are frequently used to represent a force magnitude six times the weight of the body in question. It is important to note that the symbol g is used only for the acceleration due to gravity, while G is used in aviation medicine to represent the unit of reactive force[23].

Physiological Tolerance and Performance Tolerance

One of the most important concepts in acceleration research is that of physiological tolerance, or the ability of the human subject to physiologically withstand acceleration stress. Physiological tolerance is a complex concept and encompasses a wide variety of both physiological functions and environmental factors. In reviewing the ability of man to perform a task within an acceleration environment and to maintain control over his perceptual, intellectual, and emotional faculties, it is essential that the general physiological stamina of man be considered as defining the upper limit of acceleration force within which he may be required to perform a piloting task. The concept of physiological tolerance includes all of the common physiological responses which are functions of the intensity and duration of a stress stimulus. Theoretically, therefore, the point of response may be separated from the point of no-response by a simple stimulus strength-duration curve. Figure 4 presents a summary of the authors' survey of the scientific literature and presents the current accepted physiological tolerances defined as functions of duration and G load. It should be pointed out that the points on this curve do not necessarily reflect the maximum exposures which have been experienced by human subjects.

There are some excellent reviews on physiological problems within acceleration fields in the scientific literature and the reader is referred to these for a more detailed consideration of the problem of physiological tolerance of acceleration [19, 28, 12, 14, 1, 23, 27, 4].

As pointed out in the early part of this section, the upper limits of acceleration loadings under which a given person may perform a piloting task are primarily determined by the limits of physiological tolerance. However, in addition to these physiological tolerance limits which define the maximal endpoints for safe exposure of a particular physiological system to acceleration stress, there are also performance tolerance limits which define the upper limits of reliable functioning of a particular performance-ability system under comparable acceleration exposure. Although physiological and performance tolerance limits are often functionally related, they need not be of the same magnitude since each is dependent upon its defining criteria. Performance tolerance limits are of major importance in the allocation of man-machine functions.

Prior research has indicated that as G increases, there may be an initial improvement in performance of the piloting task, followed by a gradual decline, until a performance tolerance limit is reached. Beyond this point, performance deteriorates extremely rapidly. The point of maximum efficiency is usually at a lower G than the upper performance tolerance limit; however, to date, this point has not been specified directly. Under conditions of moderate acceleration, experienced pilots may utilize motion and acceleration cues in performing their tasks and these cues, along with reasonably high concentration and motivation, may enable the pilot to do better under moderately high acceleration than under static conditions. At high G, performance proficiency deteriorates markedly. This deterioration generally reflects impairment of vision and the ability to breathe, physically strain, or a reduction of the pilot's ability to resist the physiological effects of acceleration. Summaries of the effects of acceleration upon performance may be found in Brown[2] and Chambers[4,5].

G tolerance may be expressed as a function of at least five primary acceleration variables: (a) the direction of the primary of resultant G force with respect to the axes of the human body, (b) the rate of onset and the decline of G, (c) the magnitude of peak G, (d) the duration of peak G, and (e) the total duration of acceleration from time of onset to termination. There are also other auxillary conditions which influence a human subject's tolerance. Among these are: (a) the types of endpoints used in determining tolerance, (b) the types of G protection devices and body restraints, (c) the type of environment in which a subject is tested, such as temperature, ambient pressure, noise and lighting, (d) age, (e) psychological factors such as fear and anxiety, competitive attitude, and willingness to tolerate discomfort and pain, (f) previous acceleration training and exposed accumulated effects, (g) the type of acceleration device used for exposing the subject to acceleration, and (h) muscular tensing and effort[23].

Effects of Acceleration on Vision

During exposure to high positive, negative, and transverse acceleration, visual disturbances occur. During positive acceleration, these disturbances result primarily from ischemia; however, mechanical distortion of the eye may also occur in severe cases. Generally, a period of grayout exists before blackout occurs. Grayout is characterized by general dimming and blurring. Total visual disturbance occurs approximately one G unit below the level at which blackout occurs. During exposure to high transverse acceleration, the effects on the visual system depend largely on whether the acceleration force is $+G_x$ (eye-balls-in) or $-G_x$ (eye-balls-out). When the acceleration is $+G_x$, no major visual disturbances have been reported up to loads of $+14\ G_x$ for 5 seconds at peak G. At levels between plus 6 and plus 12 G_x, however, there may be some tearing, apparant loss of peripheral vision, and difficulty in keeping the eyes open. For $-G_x$ (eye-balls-out acceleration), some pain may be experienced and small petechiae may occur on the lower surface of the eyelids. Vision may be temporarily impaired, although to date, no internal damage has been reported for accelerations as high as +15 G_x. For $-G_x$ acceleration, however, the kind of restraints provided for the anterior surface of the body is a major consideration.

The problem of seeing under transverse acceleration appears to be largely a mechanical problem, due partially to mechanical pressures on the eyes and the accumulation of tears. In addition to G amplitude and the direction of the primary G vector, the duration of peak G is of major importance. Total time in which a human subject can endure exposure to acceleration stress and maintain good vision depends largely on the system of G protection. Using a system of G protection developed by Smedal, et al[25], ithas been possible to achieve the following record runs by transverse and positive G on the AMAL centrifuge: 90 seconds at +7 G_z, 127 seconds at +14 G_x, and 71 seconds at -10 G_x. These record runs were conducted on the AMAL centrifuge using the advanced restraint system developed by the Ames Research Center. They do not necessarily establish limits of visual performance, however, since the relationship between amplitude of G and duration at peak G has not been established. For example, in an earlier experiment at AMAL, one subject, using a contour couch restraint system developed at AMAL, was able to performa visual task during an extremely high G run which took him to +25 G_x for 5 seconds.

Visual acuity decreases as the magnitude of G increases[20, 29]. This occurs during exposure to both positive and transverse acceleration. As G increases, a given level of visual acuity may be maintained by increasing the size of the target or the amount of luminance. White and Jorve[29], for example, found that at +7 G_x the target had to be twice as large as it was at one G in order to be seen. In another study, White[30] observed that a test light had to be nearly three times as bright at 4 G_z as at 1 G_z in order to be seen. Thus, a pilot's ability to read his instruments is influenced by acceleration. However, the magnitude of this effect is a partial function of the level of illumination. At high luminance, the impairment due to G is not as great as it is for the same G at lower levels of luminance. White[30] has shown that at moderate tolerance limits, increasing the amplitude of positive acceleration increases the absolute foveal visual thresholds. In most situations in which a pilot is going to be exposed to acceleration, it is important to know the amount of contrast required by the pilot in order to insure visual discrimination. As acceleration increases, an increase in contrast is required to detect a target. This has been shown in a recent study by the authors and Drs. Braunstein and White at AMAL. In this study, it was demonstrated that the minimally acceptable (threshold) contrast was greater for positive acceleration than for transverse acceleration. For example, a 16 percent contrast between the target and its background was required at +5 G_z and a 12 percent contrast was required at +7 G_x. For static conditions, an average luminance differential between target and background of approximately 8.5 percent was required for discrimination. In this particular experiment, visual brightness discrimination was studied at four levels of background luminance, at four levels of positive acceleration, and at five levels of transverse acceleration. For this study, a stimulus display generator (see Figure 5) was mounted in the gondola. This generator presented a circular test patch against a diffuse background. The display was viewed monocularly through an aperture which was 17 1/2 inches from the eye. The visual angles subtended by the circular test patch and its background were 1 degree and 28 minutes, and 8 degrees and 4 minutes, respectively. The background was generated by eight 25 watt light bulbs behind two sheets of flashed opal by a 500 watt slide projector. A frontal view of the display is shown in Figure 6. Voltage to the projector bulb was controlled by a motor-driven variac which altered the operating voltage at the rate of volts per second. A neutral density filter was placed behind the viewing aperture to produce the desired background luminance. A response button, provided to the subject, was used to indicate the appearance or disappearance of the test patch. Figure 7 shows the installation of this visual response button. After activation of the response button by the subject, the direction of rotation of the motor driving the variac which controlled test patch luminance was automatically reversed with the time between subject response and motor reversal programmed to range from 1.25 to 3.75 seconds in a random delay order. At the instant of the subject's response, the voltage across the projection bulb was stored and displayed upon a digital volt meter located at the experimenter's station. Approximately 15 responses were made during the peak G of each run. With this apparatus, it was possible to repeatedly measure a subject's ascending and descending visual discrimination thresholds. Using 6 healthy adult males with 20/20 vision, brightness discrimination thresholds were determined at transverse acceleration levels of + 1, 2, 3, 5, and 7 G_x and positive acceleration levels of + 1, 2, 3, and 5 G_z. Determinations were made at each G level with background luminance of .03, .29, 2.9 and 31.2 foot-lamberts. Figure 8 shows the observed relationship between brightness discrimination threshold and background luminance for each of the four levels of positive acceleration. Similarly, Figure 9 shows the obtained relationship between brightness discrimination threshold and background luminance for each of the 5 levels of transverse acceleration.Figure 10 shows the effects of positive acceleration (+ G_z) on brightness discrimination thresholds for perceiving the circular target against each of the four background levels. These figures show that for each of four positive acceleration conditions, the mean required contrast increased as the background luminance decreased. Also, for any given background luminance level, the higher acceleration levels required more brightness contrast. Similar results were shown for the transverse G exposures as may be seen in the figures although the differences due to background luminance were more than those due to acceleration levels. As previously mentioned, positive acceleration stress consistently imposed higher contrast requirements than did transverse acceleration. These data clearly show that marked increases in the brightness contrast required for discrimination as G increased in both the positive and transverse axes.

It is important to indicate that the physiological conditions under which the pilot performs a task such as this greatly influences the data which are obtained. For example, some of the subjects in the above study also served in an experiment to determine whether or not positive pressure breathing of 100 percent oxygen facilitates brightness discrimination at the upper G levels[9]. The subjects performed under three breathing conditions; breathing normal air, 100 percent oxygen, and 100 percent oxygen under positive pressure. Given a background luminance of .03 foot-lamberts, the subjects were required to repetitively operate a switch (see Figure 7) to maintain the target (Figure 6) at the minimally discriminable brightness contrast level. The results obtained under positive (G_z) acceleration exposures of 90 seconds duration each under acceleration loads of +1, +3, +4, and +5 G_z are shown in Figure 11. These data suggest that at the +3, +4, and +5 G_z levels, the positive pressure plus 100 percent oxygen required less visual contrast than was required under the other experimental conditions. Similar results were found for the transverse G. The contrast required for discrimination appeared to be the same for both the 100 percent oxygen and 100 percent oxygen plus positive pressure breathing conditions. Oxygen would appear to play an important role, since subjects breathing normal air under positive pressure required increasing amounts of contrast for discrimination as G increased.

The two investigations just described were presented primarily to illustrate the sort of investigations which are conducted using the AMAL human centrifuge in w hich basic sensory capacities are being studied. Similar investigations have been concerned with the effects of high accelleration upon pilot ability in such areas as discrimination reaction time, complex psychomotor performance, and higher mental abilities.

Discrimination Reaction Time Performance

In addition to influencing the pilot's ability to perceive stimuli, acceleration modifies his ability to respond to them as well. Many maneuvers which pilots must perform frequently require not only the discrimination of but the reaction to visual stimuli. In this section, we present the results of some recent work in which this latter aspect of performance was studied in some detail.

Many investigators have studied discrimination reaction time behavior on human pilots during exposure to acceleration stress. Although it is generally agreed that some acceleration environments do influence discrimination reaction time behavior, thus far it has been impossible to designate all of the underlying mechanisms which mediate these effects. During acceleration, the changes observed in reaction time could be associated with pilot impairment in a variety of physical loci. Acceleration might well reduce the capacity of the peripheral system to receive the stimulus, or of the central nervous system to process already received stimuli and to initiate discriminatory choice, as well as reduce the ability of the neuromuscular system to coordinate the motor components which translate the response into the manipulation of the appropriate control device. In addition, some studies have indicated that discrimination time under G is indirectly affected by the protective equipment and related components present in the situation in which the tests are conducted. There were also several types of discrimination reaction times, depending on the stimuli, responses, and the types of tests.

Frankenhauser[21], using red, green, and white light signals, measured complex choice reaction time during exposure to +3 G_z and found the subject took significantly longer to respond under acceleration than under normal (+1 G_z) conditions. This was true for exposures of both two minutes and five minutes duration. Her conclusion was that visual choice reaction time was increased by positive acceleration. Similarly, Brown and Burke[3] found highly significant effects of positive acceleration upon discrimination reaction time.

In contrast, relatively little information is available concerning the effects of transverse acceleration on discrimination reaction time. At our laboratory, a discrimination reaction time test apparatus was developed which consisted of four small stimulus lights, a small response handle containing four small response buttons, and a programmer device which could present a large variety of random sequences to subjects on the centrifuge[11]. Tests conducted on discrimination reaction time behavior of subjects statically and while submerged in water showed that subjects could respond steadily and reliably on this device. A typical example of data from this experiment is shown in Figure 12. However, mounting the device upon the centrifuge revealed that transverse acceleration exposures significantly influenced performance of the discrimination reaction time tasks. Figure 13 shows the installation of this apparatus in the centrifuge. As each of the lights came on, the subject was required to press the associated finger button with his right hand as fast as he could. Both the automatic program which activated the stimulus lights and the subject's responses were fed to an analog computer where initial data reduction was accomplished. Following pre-acceleration training to a stable baseline performance level, each subject received three blocks of twenty-five trials each while exposed to 6 G_x for five minutes. Each subject received three such acceleration trials. Since speed and accuracy are both involved in this type of response behavior, times and errors were normalized and added. The results are shown in Figure 14. This figure shows that during the first block of twenty-five trials, the average response scores were slower than the overall average. During the second series of trials, the response scores were even slower than for the first block of trials. For the third block of trials under G, however, performance was significantly improved over that exhibited during the earlier trials. The results of this study suggest that acceleration initially impaired performance during the first and second series of acceleration trials but that by the third series of trials, the subjects had learned to maintain their physiology and performance under acceleration stress and, consequently, their discrimination reaction time scores improve, suggesting that learning how to perform during exposure to acceleration stress is a primary factor in determining pilot performance ability. It may well be that the process of learning could account for some of the differences in findings which have been reported by earlier investigators who contrasted static and dynamic conditions with taking into account the possibility of rapid adaptation to the experimental conditions.

Another approach to reaction time investigation involves the use of an auditory rather than a visual stimulus in order to avoid the problem of visual interference which is known to accompany acceleration. One such task[17] required the subject to add pairs of numbers which he heard via an auditory magnetic tape system and then to describe the sum by pressing the small odd and even response buttons which were mounted upon his left and right hand grips, respectively. Primarily, work with this apparatus during positive G_z exposures to grayout levels indicated that the time required to make these responses increased during exposure to positive acceleration.

Complex Psychomotor Performance

The ability to perform a complex psychomotor test is impaired in most cases by acceleration. A typical example of a relatively simple case is shown in Figure 15 in which the skill with which six subjects performed the horizontal and vertical components of a tracking task response at one minute intervals during each of two +8 G_x trials is plotted as a function of acceleration. The acceleration profile is dotted at the bottom of the graph. During these test runs, the subjects operated a control device in response to the coordinated pitch and roll tracking maneuvers which were pre-programmed and presented to the subject by means of the oscilloscope. The apparatus and the contour couch on which the subject was accelerated is shown in Figure 16. The graph shows steady performance levels for the horizontal and vertical components of the tracking tasks prior to exposure to acceleration. When peak G was reached, decrements in both components were obtained but as acceleration receded to normal, both performance components rapidly returned to the normal skill level. Figure 15 also shows the effects of acceleration following submersion in water to the neck level for 12 hours[11]. These subjects showed approximately the same performance curves, even after an unusual and prolonged intervening experience, suggesting the relative stability of the control decrement associated with acceleration stress.

In other recent work at our laboratory the authors, in cooperation with Mr. Creer and Dr. Smedal of NASA, used the centrifuge to simulate sustained reentry tracking control problems. It was demonstrated that well trained test pilots could successfully perform a moderately complex tracking task while being subjected to a relatively high and varied acceleration for prolonged periods of time. A special restraint system[25] was used to minimize physiological discomfort during this particular study. Tracking efficiency was calculated in percentage units based on the accumulated tracking error divided by the accumulated excursion of the target in this study. Pitch and roll control inputs were made with a small two axes pencil controller and the yaw inputs were made with the toe pedal which was operated by flexion and extension of the foot about the transverse axes of the ankle joints. The restraint equipment used in this study is shown in Figure 17. In this particular study the rate of onset for all the accelerations was approximately .1 G per second. Each tolerance run was preceded by a static run which was intended to serve as the baseline for the prediction of performance under acceleration. Tracking performance was impaired at the high G levels; however, the pilots were able to maintain proficiency above the minimum levels considered necessary to continue the run, as determined from a percentage scale of -100 to +100 percent derived from the division of actual control output by required output. Smedal, et al[26] have published some of the results from this experiment and have related these performance boundaries to the accelerations anticipated during reentry from both circular and parabolic (lunar return) orbits. They concluded that a man properly restrained can withstand the acceleration stress imposed by reentry from minimal circular orbits. The subjective findings obtained during this study emphasized the visual, cardiovascular, and respiratory effects accompanying acceleration. One major advantage of $-G_x$ acceleration over $+G_x$ was indicated by this study, namely that during $-G_x$ acceleration, the forces of acceleration assist in breathing by increasing the interior and posterior diameter of the chest, the normal functions of inspiration, whereas during $+G_x$ these same forces impede inspiration through chest compression.

In a more recent study with NASA/Ames, conducted at the AMAL centrifuge, Chambers and Smedal tested pilots able to reach phenomenal transverse acceleration endurance records and still maintain a relatively high level of performance proficiency on a complex tracking task. The most striking centrifuge runs for $+G_x$ steady state acceleration was +14 G_x for 127 seconds. The outstanding run for $-G_x$ steady state was -10 G_x for 71 seconds. This was accomplished by using the special restraint system shown in Figure 18.

In another AMAL study, test pilots who had performed a complex tracking test at transverse acceleration levels of 1, 3, 5, 7, 9, 12 and 15 G_x were asked to estimate the amount of performance decrement which occurred under each acceleration load. In making their estimations, the pilots used their performance at 1 G as the base referant and attempted to contrast their performance at other levels against their own 1 G performance. The average estimates for performance decrement are shown in Figure 19. At the 12 and 15 G_x levels, the outstanding problems which the pilots reported they encountered were impairments of vision, difficulty in breathing, as well as difficulty in operating the control device used.

To study the effects of acceleration on the ability of pilots to perform control tasks during simulated boost accelerations, Chambers and Holloman exposed pilots to staging acceleration profiles characteristic of both a two-stage launch vehicle and a four-stage launch vehicle. The analog computer facility used generated and converted into vehicle dynamics the pilot's display and control problem as well as the commands for driving the centrifuge. In this particular series of runs, the longitudinal mode (pitch) required almost continuous control whereas the yaw control required only monitoring and correcting for disturbances. Figure 20 summarizes some of the findings and provides an example of pilot performance in which some features of the piloting task were greatly affected by acceleration while others were not. In this particular study, the pilots indicated that they were unable to concentrate on more than one or two things at the same time at high G. Thus, they found it necessary to neglect some parts of the four dimensional tasks shown here while under acceleration. Subjective ratings made by the pilots showed that under low accelerations, only normal physical effort was required to perform the launch control task. However, at the highest acceleration tested, 100 percent effort was required. The 100 percent effort rating was applied to a series of special runs which sampled abilities to perform under acceleration loads extending up to as high as 15 G. Such limit testing only augmented the primary portion of this investigation which involved a computer controlled simulation of a hypothetical four-stage launch vehicle. Figure 21 shows a typical launch curve for this simulated condition. The pilot's task was to fly the vehicle through the orbital injection "window". At the acceleration level studied (all below 7 G_x), there appeared to be little effect of the acceleration on the control task as determined by the pilot's ability to manage the primary control quantities. These results are shown in Figure 22.

Effects of Varying the Type of Control Device Used

In addition to both the direct effects of acceleration upon human performance and the less obvious interactions between performance and acceleration already mentioned, there is a growing body of information pertaining to the somewhat secondary role that other flight conditions play in determining a pilot's performance during exposure to acceleration[7,8]. An important example of this is the contribution made by the type of control device that the subject is using. Control devices have many characteristics which may influence performance under acceleration conditions. Some of the variables found to be important are: (a) the relationship between the axes of controller motion and the acceleration vectors imposed upon the pilot's hand, (b) the number of axes of motion, (c) the stick force gradient along each mode of control, (d) the centering characteristics along each mode of control, (e) the basic location of the control device, (f) controller breakout forces, (g) control device friction, (h) damping characteristics, (i) the magnitude of control throw, (j) control response time, (k) control harmony, (l) cross coupling, (m) the amount of kinetic feedback provided by the controller, (n) controller shape and size, and (0) the dynamic and static balancing of the control device. The combination and interactions of these characteristics requires a very complex and extended discussion. Therefore, the present report will cover only those aspects found to contribute most to controllability.

In the course of early simulations of proposed space vehicles, several types of right hand side controllers have been tested. Figure 23 presents a diagram of four of these controllers: a three axis balanced controller with all three axes intersecting; a three axis controller (unbalanced) having none of these three axes intersecting; a three axis balanced controller; a finger tip controller having two intersecting axes with yaw operating via toe pedals; and a two axis controller with axes that do not intersect, coupled with toe pedals for yaw control. In Figure 24, the effects of two specific acceleration fields upon pilot performance during the pitch and roll maneuvers involved in a tracking task are shown for each of the four types of controllers. While the pilots performed in one acceleration field, their error performance on all four controllers was essentially the same. However, when these same pilots flew the same problem under a different acceleration vector, performance on Type II controller greatly increased while performance on the other two controllers remained essentially unchanged. A simular change in G field resulted in an increment in error for Types II and III controllers and reduction in error for Type IV, resulting in a shift in rank order of the controllers. The differential effects upon performance induced by different types of acceleration controllers are shown in Figure 25. Here, the mean tracking efficiency scores for test pilots who perform the same tracking tasks using each of the four different t ypes of side arm controllers within given acceleration fields and under varying amounts of cross coupling and damping are shown. This figure shows not only the effect of using different specific G fields on particular tracking tasks but also illustrates the effects of damping and cross coupling when the effects of acceleration are held constant.

In studying the effects of acceleration, one must also consider the complexity of the task to be performed by the pilot since t ask complexity is magnified under G [2]. Basic research upon the effects of high G upon complex task performance is frequently complicated by the need to control the numerous variables associated with task difficulty. Aerodynamic stability, damping frequency, time constant, and other vehicle response characteristics strongly interact with acceleration to determine pilot performance at high G. If the simulated vehicle is highly stable and well damped within the desired frequency ranges, the pilot may find performance under high G relatively easy. However, the same general piloting task may be impossible at lower G levels with a simulated vehicle having less desirable aerodynamic characteristics.

Effects of Acceleration on Higher Mental Abilities

To date, there is a severe lack of reliable and valid tests of higher mental activities which can be administered within the basically restrictive and time-limited conditions encountered in centrifuge operation and still retain the measurement sensitivity required. A way to monitor the intellectual functioning of the subject while he is being exposed to acceleration conditions is sorely needed. Several reviews of this problem have been presented [5, 6, 7, 24]. It is a generally accepted fact that exposure to high or prolonged acceleration may produce confusion, unconsciousness, disorientation, memory lapse, loss of control of voluntary movements, or prolonged vertigo. However, the tolerance limits of basic intellectual functions are unknown, and there is very little quantitative information which would indicate which of the specific higher mental skills may suffer impairment.

An astronaut or scientific observer during some phases of flight may be required to perform tasks such as monitoring, reporting, flight guidance, and other tasks which require immediate memory and the processing of information. To date, there is no conclusive information available regarding the effects of acceleration upon the basic intellectual abilities required for such functions, i.e., immediate memory and the ability to process information.

Using the human centrifuge at AMAL, Ross and Chambers conducted a study on the effects of both positive and transverse acceleration upon the ability to perform a task which placed demands upon these psychological abilities. A continuous memory testing apparatus was developed which could be used under both static and acceleration conditions. This test required the continuous and repetitive memorization of a portion of a sequency of random symbols. As each symbol occurred, the subject was required to compare it with his memory of the s ymbol which had been presented to him two, three, or four presentations previously. New symbols appeared continuously so that the subject continuously had to f orget earlier symbols as he added the new ones. Basically, this task involved both the immediate memory and the facility for handling an "information load" of symbols under conditions in which opportunity for symbol interference was at a high level. The "running matching memory" task used was simple to grasp and administer but difficult to perform without error. The subject was presented with a plus or a minus sign by mans of a digital display tube mounted in front of him and was required to judge whether the sign he saw was the "same" as "or different from" the sign he had seen either 2, 3, or 4 presentations previously. These three memory spans were interspersed throughout a test series and were known as the 2-back, 3-back, and 4-back condition, respectively. Simultaneous with the presentation of the plus or minus sign, the subject saw the numeral 2, 3, or 4 in another tube, indicating whether a 2-back, 3-back, or 4-back match was to be performed. The subject made the required matches for each sign as it appeared. Each sign was presented for four seconds with a one-second interval between presentation. A series of fifty signs was presented within any given run. The G-level selected for investigation was 5 transverse G for 5 minutes.

Data analysis indicated no significant differences in percentage of correct memory matches between static and G conditions. Twenty-four subjects completed the required series of four 5 G runs of five minutes each, however, there was an increase in the latency betweenpresentation and time of response. Also, the subjective comments concerning performance on this task did not correlate well with the actual quantitative measures (Figure 26). The number correct for each series was converted into a percentage since the number of matching responses made were not quite the same for each condition — 48 matches for a 2-back condition, 47 matches for a 3-back condition and 46 matches for a 4-back condition. Subjects reported that their performance deteriorated under G and they regarded this exposure as an extremely stressful experience.

Related research has suggested that the previously discussed measures of discrimination reaction time reflect intellectual performance, and that one may use such measures as a general indicator of higher mental functioning. The results of some studies at AMAL suggested not only that discrimination time was impaired under G, but also for some time after the termination of G. Figure 27 summarizes the results of one such study. In this figure, the abscissa is quantified in standard-error-of-mean units. Using a one tailed t-test, it was shown that performance was significantly impaired not only under +6 G_x acceleration but that this decrement persisted after the centrifuge run was completed and the pilot returned to the normal (+1 G_x) acceleration field.

In a more recent study conducted at AMAL, a second attempt was made to explore higher mental functioning of human subjects exposed to acceleration stress. The task required the subject to monitor two small display tubes which were located directly in front of his normal line of vision. The left-side tube presented numbers, and the right-side tube presented plus and minus symbols. The task was to continuously make matches for these two presentations simultaneously as the runs proceeded and to select one of two buttons to indicate whether both the number and symbol which were then appearing were the same as or different from those which had occurred a specified number of trials previously. Nineteen male subjects volunteered to perform this running matching task while sustaining transverse accelerations of 1, 3, 5, 7, and 9 G's. Each test was 2 minutes 18 seconds long. The results of the experiment suggested that proficiency in immediate memory was maintained at least through 5 transverse G. However, at 7 G and 9 G, some impairment in immediate memory was observed.

During prolonged exposure to acceleration, the continuous concentration necessary for performance maintenance is difficult, fatiguing, and boring. For example, during an extended 2 G centrifuge run which lasted for 24 hours, the subject started out with a somewhat detailed set of procedures to follow in making medical observations upon himself, recording his subject comments, and writing and typing [13, 15]. However, the subject found that, in spite of his initial high resolves, he took naps and listened to the radio instead and suffered primarily from boredom and fatigue. Areas of contact with the chair in which he was seated were the sources of the greatest localized discomfort. At 16 hours elapsed time, the subject reported the onset of aesthenia of the ring and little finger and outer edge of the palm of the left hand. The subject found it impossible to maintain his originally prescribed maintenance and observation schedules.

In an attempt to obtain specific information concerning the effects of extended, moderate acceleration upon higher mental abilities, a shorter study (+2 G_x for 4 hours) was performed. The subject was secured in a contour couch and required to perform the two-symbols running matching memory task previously described every 10 minutes. The subject was able to perform this task throughout the entire period with only minor performance impairment. Furthermore, task performance during the 4-hour acceleration exposure was not significantly different from performance either before or after the centrifuge run. Throughout the test period, task performance was highly correlated with the pilot's subjective estimations of his proficiency.

The Effects of Acceleration Upon Specific Mission Tasks

The performance measurements described thus far have emphasized the effects of acceleration(s) upon the expression of rather general psychological and/or psychomotor abilities. Recent data indicate that even highly specific and well practiced skills are not immune to the effects of acceleration. For example, performance measures collected during a recent astronaut training program, Mercury Centrifuge IV, conducted jointly by NASA and AMAL, revealed several significant effects of dynamic simulation upon pilot performance and response.

Two primary modes of centrifuge control may be used during such a dynamic simulation of the accelerations associated with space vehicles and high-speed aircraft: (1) open-loop and (2), closed-loop centrifuge command systems. In open-loop control, the centrifuge commands are preprogrammed either on punched tape or within the computer proper. These programmed commands are not subject to pilot control short of termination of the simulation by activation of the abort switch. In closed-loop centrifuge control, the pilot overlays the effects of his control actions upon the preprogrammed acceleration profile. The actual accelerations imposed upon the pilot thus reflect not only expected system characteristics but pilot performance as well.

By combining the control motion outputs with the preprogrammed acceleration commands, the computer's coordinate converter system presents drive signals to the centrifuge which directly reflect the pilot control outputs.

During both modes of operation, the pilot's instruments and panel displays, particularly those concerned with the vehicle's rates and attitudes, are usually controlled by a closed-loop system to provide the pilot with immediate and continuous feedback regarding his control activities. However, certain displays such as event-times and/or sequences are often controlled in an open-loop manual or preprogrammed fashion. Figure 28 is a schematic presentation of the centrifuge/computer interface during open-loop acceleration command (solid lines) and closed-loop panel display (open lines).

For the simulation to be discussed here, a punched-tape program was used to drive the centrifuge in an open-loop command fashion. The side-arm controller, the computer, the instrument panel, and the pilot formed a closed-loop system of display activation. The acceleration profile (Figure 29) was a real-time approximation of the accelerations predicted for the orbital mission. For the runs to be discussed here, the orbital time was collapsed with retrofire closely following the completion of the boost phases and capsule turnaround. During static simulations, only the closed-loop display system was activated, thus providing a real-time simulation of the control tasks with their associated panel displays and telepanel sequence indications. The dynamic simulations used the same displays and controller tasks but were accompanied by the open-loop driving commands to the centrifuge which superimposed the acceleration profile upon these piloting tasks.

The data to be discussed here are based upon a series of twelve simulations (four static and eight dynamic) which were flown by each of the seven astronauts. These twelve simulations sampled performance under most of the possible combinations of acceleration, suit, and cabin pressurization conditions.

During such simulation programs, pilot performance is continuously monitored and evaluated. The facility primarily responsible for this phase of simulation assessment, the Engineering Psychology Laboratory, is equipped with an analog computer and associated equipment including graphic plotting, digital print out, and FM-tape recording capabilities. The primary unit of measurement is the analog error as represented by the voltage differential between inputs representing the existing controller and/or vehicle positions and the preprogrammed inputs representing the appropriate or desired attitudes. Figure 30 graphically summarizes the techniques of analysis and summarization available within this facility. This figure also portrays the capability for discrete task and event recording as well as for recording the latency of pilot response to displayed event indications.

In the course of an orbital mission of the Mercury type, in addition to his other duties the astronaut is required to monitor the telelight portion of the capsule instrument panel and to confirm booster and/or capsule response(s) to a programmed sequence of flight events. If an event is not performed at the scheduled time, the telelight panel displays a RED-LIGHT condition (indicating capsule receipt of the event command not accompanied by internal confirmation of the required operations) or a NO-LIGHT condition (indicating panel and/or internal telemetry system failure). It may then be necessary for the pilot to manually initiate (over-ride) the operation(s) normally instigated by the automatic, programmed circuitry. During training simulations such as the recent Mercury IV program, an externally mounted control panel (Figure 31) is used to monitor and control the inputs to the telelight display which is along the left side of the pilot's control panel (Figure 2). When RED-LIGHT or NO-LIGHT indications were given, a .01-second timer recorded the time between normal automatic instigation and its associated telepanel warning and the performance of the required over-ride by the pilot.

It should be noted that only one of the required telepanel over-rides, manual operation of the Escape Tower Jettison ring, occurred under G. Even this over-ride involved only moderate acceleration loads of approximately 2 G. However, for purposes of the following discussion, telepanel responses which were made in the course of simulations involving centrifuge acceleration are classed as Dynamic responses even though little or no acceleration loads were present at the actual moment of response.

The following three general categories of acceleration effects were among those noted during the course of this program:

1. Acceleration resulted in the insertion of specific control inputs of which the pilots were often unaware.

2. Acceleration generally disrupted the timing and precision of pilot control.

3. Discrete task functions such as an operation over-ride were affected by accelerations which preceded and/or followed them though the operations themselves were performed under minimal acceleration loads.

These three effects of acceleration have been treated generally elsewhere [5, 10]. The purpose of the following discussion is to show how these general effects are expressed within a specific system configuration.

Inadvertent Control Inputs

At rest, a side-arm controller such as that used in the Mercury capsule is adjusted to maintain the central position in all axes and is balanced to retain this inactive, central position under acceleration. Any displacement of the controller, in excess of the central inactive range or "dead-band", serves to activate the capsule's control jets (nozzles) which impose reorientation accelerations upon the capsule. Dynamic conditions are not infrequently accompanied by controller deflections of which the pilot is unaware. Any control deflections occurring without the knowledge and intent of the pilot can seriously complicate the control task. Such inadvertent control inputs can even result in complete loss of control, since the limitations upon nozzle velocity are such that inadvertent inputs can easily reach sufficient magnitudes and/or durations to impose reorientation rates beyond those which can be damped within the time limits established by the mission profile. These inadvertent inputs often mirror the acceleration profile under which the control tasks are performed. Figures 32, 33, and 34 are representative examples taken from actual records, which display such inputs in the roll, yaw, and pitch axes respectively. As illustrated by these sample records, these involuntary control deflections generally appear in a single axis though Figure 35 illustrates the less frequently observed simultaneous appearance of inadvertent inputs in two axes: roll and yaw. The fact that the pilots are often unaware of such inputs is illustrated by the fact that the excessive fuel utilization associated with such sustained deflections was interpreted upon several occasions as a simulated fuel leakage problem and not as the result of controller activation.

General Control Effects

In addition to inadvertent inputs which accompany acceleration, other more general effects of dynamic conditions may be observed. Acceleration appears to generally reduce the sensitivity and timing of all controller movements. Figures 36 and 37 are sample portions of the recorded static and dynamic performance of the same pilot taken within twenty minutes of each other. These records serve to illustrate the general effects of accelera- upon the frequency and amplitude of control movements. Certainly no one should be surprised to learn that the task of flight control is made more difficult by the imposition of acceleration forces. However, the authors are willing to risk the accusation of pedantry in order to emphasize the extent of such effects as well as the need to assess such effects by dynamic simulation before attempting to estimate actual flight performance parameters. The fact that dynamic conditions do affect pilot effectiveness is amply illustrated by the percentage of simulated reentries in which the rates of capsule oscillation were kept within the limits of control capability under static and under dynamic conditions (Figure 38). Since the simulations upon which these percentages are based imposed pitch and yaw oscillation rates drawn from the upper extreme of the range of expected values, and insofar as Friendship 7 successfully reentered even though the oscillations were quite large, these percentages do not represent the probability of success of an actual Mercury flight or similar missions. However, these figures may be considered representative of the general effects of acceleration upon the ability of pilots to dynamically perform control tasks which they perform easily under static conditions.

As previously mentioned, the tendency to use less discrete, more frequent control inputs (Figure 37) under dynamic conditions is associated with an overall increase in fuel utilization. A most important aspect of this relationship rests upon the fact that differential rates of fuel usage were observed even when no significant differences in adequacy of control as measured by integrated attitude error were present. As previously indicated, pilot ability to damp the reentry oscillations in pitch and yaw was reduced under dynamic simulation. In contrast, control capability in the roll axis was not significantly affected by dynamic reentry accelerations. Therefore, roll control during reentry can be used to illustrate this dynamic effect under conditions of equivalent error. Figure 39 illustrates not only the correlation between incurred roll rate error and compensatory fuel usage [fuel used/lbs. = k·(.00012·Integrated Roll Rate Error in Degree seconds/sec.)]but also that fuel utilization was approximately 33 percent greater under dynamic (k = 1.328)than under static conditions (k=1.00) though integrated error was of the same approximate magnitude under both conditions. It is highly unlikely that the additional fuel usage predictable from these results would interfere in any way with a mission such as the Mercury three orbital flight since adequate fuel reserves were available. However, it is conceivable that the failure to take into account a potential increment in fuel expenditure in excess of 30 percent could have serious consequences in future missions of longer duration. Data of this nature emphasize the advisability of obtaining both dynamic and static performance evaluations for any system configuration before placing estimated values upon such design parameters as required fuel reserves.

Other aspects of pilot performance also confirm the value of dynamic performance evaluations. As may be seen in Figure 40, the hard suit (5 psi differential pressure) conditions resulted in a reduction in relative piloting performance as measured by the percentage of the reentry simulations in which capsule oscillations were successfully damped during static simulation of the reentry control task, but appeared to assist performance under dynamic conditions. The performance values presented in this figure are not absolute but represent relative performance using the conditions of STATIC/SOFT-SUIT, under which control most often retained throughout the reentry profile, as a base-line referent. The additional forearm support provided by the pressurized suit appeared to reduce the frequency and/or magnitude of the previously described inadvertent inputs which accompanied dynamic simulation. As the tendency to insert such inputs was reduced through practice, the stabilization provided by the inflated suit appeared to become less and less of an advantage and the interaction between suit and run conditions was markedly less during the latter stages of training. Verbal reports obtained toward the end of the training program indicated that the pilots considered SUIT-HARD conditions more uncomfortable and perhaps even less effective.

Discrete-Task Responses

As can be seen in Figure 41, the overall mean response time to telepanel indications was not affected by acceleration. However, dynamic simulation did significantly increase response variability ($F = 2.9$, $p < .05$). This latter finding could be of operational significance in system configurations requiring precise manual sequencing on the part of the pilot. Also, of interest, is the observation, implied by the large variance in the response times obtained under acceleration, that individual pilots react differentially to the stress(es) of dynamic acceleration conditions. Table 1, which summarizes the performance of the five astronauts for whom complete data were available, serves to demonstrate the extent of this differential reaction. As shown in this table, pilots No. 1 and No. 4 displayed shorter reaction times under dynamic conditions to all but one malfunction indication. At the other extreme, the response times of pilot No. 2 to all indications were retarded during dynamic simulation. Under acceleration, the other two pilots exhibited consistent but mixed response time alterations as a function of the indication involved.

Table 2 summarizes the relative response times to the NO-LIGHT and RED-LIGHT panel indications under both static and dynamic conditions. As can be seen, response time was considerably longer when no indication was given than when improper sequencing was displayed to the pilot by the RED-LIGHT panel indication. Response variability was significantly ($F = 88.53$ $p < .01$) greater under the NO-LIGHT condition. There was some tendency for acceleration to increase reaction time to the NO-LIGHT condition more than for RED-LIGHT presentations though response variability was such that this interaction was not found to be statistically significant. However, additional evidence of an interaction between type of indication and acceleration is available from a tabulation of totally missed telepanel indications. Upon only seven occasions did the pilots fail to make any response whatever that would indicate recognition of an existing sequencing problem. All seven of these response failures occurred under the NO-LIGHT and Dynamic conditions.

Average response times were not significantly affected by the change in altitude simulated by gondola evacuation (Figure 42). Average override latency was 3.64 seconds at sea level pressure (14.7 psi) and 4.68 seconds when gondola pressure was reduced to 5 psi. As shown in Figure 43, the pressurization of the suit did not significantly alter response time. Average latency was 4.28 under SUIT-HARD conditions and of 3.68 seconds with the soft suit.

Summary and Conclusions

This report attempts to consolidate the findings of both prior and recent research in the area of acceleration effects upon performance and to relate these findings to basic piloting behaviors. The decrements in the visual, psychomotor response, and intellectual processes which have been found to accompany acceleration stress are quantified where possible. Both transverse and positive accelerations have been shown to raise the level of contrast required for visual brightness and to reduce general acuity at acceleration loads well below those which result in gross visual impairment. Similar impairments in discrimination response rates are also discussed. The techniques thus far used to assess higher mental ability under acceleration are presented as are some of the problems which complicate such measurements. Data from such studies are presented to illustrate the reduction in immediate memory and information processing capabilities of pilots experiencing both high-level, short term and moderate, extended accelerations.

The known effects of acceleration upon the ability of pilots to "fly" both simple and whole-system simulations are cataloged with special attention given to the ways in which such variables as system complexity, controller construction, restraint and life-support equipments, and subject learning serve to augment or reduce these effects.

Brief introductions describing the relevant nomenclature, simulation techniques, and data handling processes precede the discussion of research findings.

References

1. Bondurant, S. Transverse G. Prolonged Forward, Backward, and Lateral Acceleration. In Gauer, O. H. and Zuidema, G.D. (Eds). Gravitational Stress in Aerospace Medicine, pages 150-159, Boston: Little, Brown & Co. 1961.

2. Brown, J.L. The Physiology of Acceleration-Performance. In Gauer, O.H. and Zuidema, G.D. (Eds). Gravitational Stress in Aerospace Medicine, pages 90-114, Boston: Little, Brown & Co., 1961.

3. Brown, J.L. and Burke, R.E. The effect of positive acceleration on visual reaction time. J. Av. Med. 29: 48-58, 1958.

4. Chambers, R.M. Control Performance under Acceleration with Side-Arm Attitude Controllers. Aviation Medical Acceleration Laboratory, U.S. Naval Air Development Center, Johnsville, Pa., Report NADC-MA-6110, 27 Nov 1961.

5. Chambers, R.M. Human Performance in Acceleration Environments. In Burns, N.M., Chambers, R.M., and Hendler, E. (Eds). Human Behavior in Unusual Environments. Chicago, Ill.: Free Press, 1962. In press.

6. Chambers, R.M. Dynamic Simulation for Space Flight. In Chambers, R.M. and Smith, B.J. (Eds). What Needs Doing About Man-in-Space? A discussion at the 1959 American Psychological Association Convention, Phila., Pa., The General Electric Co., 1959.

7. Chambers, R.M. Problems and Research in Space Psychology. Aviation Medical Acceleration Laboratory, U.S. Naval Air Development Center, Johnsville, Pa. Report NADC-MA-6145, 24 Apr 1962.

8. Chambers, R.M. and Nelson, J.G. Pilot Performance Capabilities during Centrifuge Simulations of Boost and Reentry. American Rocket Society Journal 31 (11): 1534-1541, 1961.

9. Chambers, R.M., Augerson, W.S., Kerr, R., and Morway, D. Effects of Positive Pressure Breathing on Performance and Physiology during Acceleration. Aerospace Med. 33: 1962.

10. Chambers, R.M. and Lathrop, R.G. Considerations in Testing for Intellectual Impairment due to Acceleration. Paper presented at the Annual Meeting of the American Medical Association, Military Medicine Division, New York, June 1961.

11. Chambers, R.M., Morway, D.A., Beckman, E. L., DeForest, R. and Coburn, K.R. The Effects of Water Immersion on Performance Proficiency. Aviation Medical Acceleration Laboratory, U. S. Naval Air Development Center, Johnsville, Pa. Report NADC-MA-6133, 22 Aug 1961.

12. Clark, C. C. Acceleration and Body Distortion. The Martin Company, Baltimore, Md. (Life Sciences Department), Nov 1961, Report ER 12138.

13. Clark, C.C. and Gray, R.F. A Discussion of Restraint and Protection of the Human Experiencing the Smooth and Oscillating Accellerations of Proposed Space Vehicles. Aviation Medical Acceleration Laboratory, U. S. Naval Air Development Center, Johnsville, Pa. Report NADC-MA-5914, Oct 1959.

14. Clark, C.C. and Faubert, D. A Chronological Bibliography on the Biological Effects of Impact. The Martin Company, Life Sciences Department, Baltimore, Md. Report ER 11953, 27 Sep 1961.

15. Clark, C.C. and Hardy, J.D. Preparing Man for Space Flight. Astronautics 18-21 and 88-90, Feb 1959.

16. Clark, C.C., Hardy, J.D. and Crosbie, R.J. A Proposed Physiological Acceleration Terminology with an Historical Review. In Human Acceleration Studies, Publication 913, pages 7-65. National Academy of Sciences, National Research Council, Washington, D.C., Panel on Acceleration Stress for the Armed Forces-NRC Comm. on Bio-Astronautics, 1961.

17. Cope, F.W. and Jensen, R. Preliminary Report on an Automated System for the Study of Higher Mental Function in the Human Subjected to Acceleration Stress. Aviation Medical Acceleration Laboratory, U.S.Naval Air Development Center, Johnsville, Pa. Report NADC-MA-6113, 8 Sep 1961.

18. Dixon, F. and Patterson, J.L., Jr. Determination of Accelerative Forces Acting on Man in Flight and in the Human Centrifuge. In Gauer, O.H. and Zuidema, G.D. (Eds.) Gravitational Stress in Aerospace Medicine, pages 243-256, Boston: Little, Brown & Co., 1961.

19. Eiband, A.M. Human Tolerance to Rapidly Applied Accelerations. NASA Memorandum 5-19-59E, June 1959.

20. Frankenhauser, M. Effects of Prolonged Radial Acceleration on Performance. Reports from the Psychological Laboratory, University of Stockholm, No. 48, pages 1-10, 1957.

21. Frankenhauser, M. Effects of Prolonged Gravitational Stress on Performance. Acta. Psychologica 14: 92-108, 1958.

22. Gauer, O.H. Definitions: Magnitude, Direction, and Time Course of Accelerative Forces. In Gauer, O.H. and Zuidema, G.D. (Eds.) Gravitational Stress in Aerospace Medicine, pages 10-15, Boston: Little, Brown & Co., 1961.

23. Gauer, O.H. and Zuidema, G.D. Gravitational Stress in Aerospace Medicine. Boston: Little, Brown & Co., 1961.

24. Galambos, R. Psychological Testing of Subjects undergoing Acceleration Stress. In Reports on Human Acceleration, Publication 901, pages 13-54. National Academy of Sciences, National Research Council, Wash., D. C., 1961.

25. Smedal, H.A., Stinnett, G.W. and Innes, R.C. A Restraint System Enabling Pilot Control under Moderately High Acceleration in a Varied Acceleration Field. NASA Tech. Note D-91: 1-19, May 1960.

26. Smedal, H.A., Creer, B.Y. and Wingrove, R.C. Physiological Effects of Acceleration Observed during a Centrifuge Study of Pilot Performance. NASA Tech. Note.D-345, Dec 1960.

27. Stapp, J.P. Human Tolerance to Severe, Abrupt, Acceleration. In Gauer, O.H. and Zuidema, G.D. (Eds) Gravitational Stress in Aerospace Medicine, Pages 165-188, Boston: Little, Brown & Co., 1961.

28. Swearingen, J. J., McFadden, E.B., Garner, J.D. and Blethrow, J.G. Human Voluntary Tolerance to Vertical Impact. Aerospace Med. 31: 989-998, 1960.

29. White, W.J. and Jorve, W. R. The Effects of Gravitational Stress upon Visual Acuity. USAF, WADC-TR-56-247.

30. White, W.J. Variations in Absolute Visual Thresholds during Accelerative Stress. Wright Air Development Center, Wright-Patterson AFB, Ohio, WADC-TR 58-334, 1958.

Table 1

Malfunction Indication

Pilot Number	Jett. Tower	Sep. Cap.	Jett. Retros	Ret. Scope	.05 G	Main Chute
1	-	+	+	+	+	+
2	-	-	-	-	-	-
3	-	-	+	-	-	+
4	+	+	+	-	+	+
5	-	-	+	-	+	+

(+) = Pilot took longer to respond under STATIC than DYNAMIC conditions.

Table 2

Average Response Times as a Function of Indication Mode and Acceleration

	RED-LIGHT	NO-LIGHT	TOTAL
STATIC	2.102	5.126	3.383
DYNAMIC	2.236	6.683	3.537
TOTAL	2.733	5.988	

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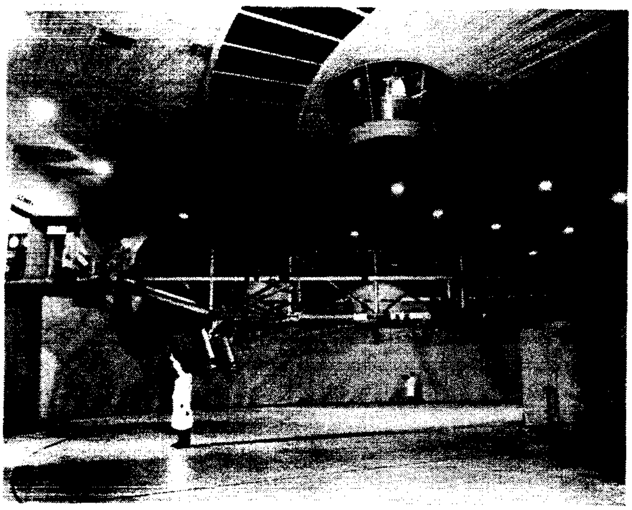
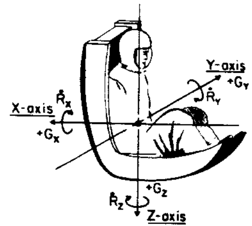


FIGURE 1. The AMAL centrifuge chamber showing the 50-foot arm, the gimbal mounted gondola, the control blister, and the loading platform.

FIGURE 2. Mercury Astronaut in AMAL centrifuge gondola during training and simulation in preparation for Mercury Redstone and Mercury Atlas space flights.

PHYSIOLOGICAL DESCRIPTION OF ACCELERATION



(Body Fluids, Heart Displacement, With Respect to Skeleton)

Linear Acceleration Modes

Description of Heart Motion

Actual	Other Descriptions			Symbol	Unit
Towards spine	Eye-balls-in	Chest-to-back	Backward facing	$+G_x$	g
Towards sternum	Eye-balls-out	Back-to-chest	Forward facing	$-G_x$	g
Towards feet	Eye-balls-down	Head-to-foot	Headward	$+G_z$	g
Towards head	Eye-balls-up	Foot-to-head	Footward	$-G_z$	g
Towards left	Eye-balls-left	——	Rightward	$+G_y$	g
Towards right	Eye-balls-right	——	Leftward	$-G_y$	g

$$NG = \frac{a}{g} = N_1 G_x + N_2 G_y + N_3 G_z$$

$$N^2 = N_1^2 + N_2^2 + N_3^2$$

Angular Acceleration Modes

Acceleration about X-axis (roll axis)	$\dot{R}_x$	rad/sec²
Acceleration about Y-axis (pitch axis)	$\dot{R}_y$	rad/sec²
Acceleration about Z-axis (yaw axis)	$\dot{R}_z$	rad/sec²

(Angular acceleration is positive or negative by right hand rule)

FIGURE 3. Physiological displacement nomenclature used in describing the physiological effects of acceleration.

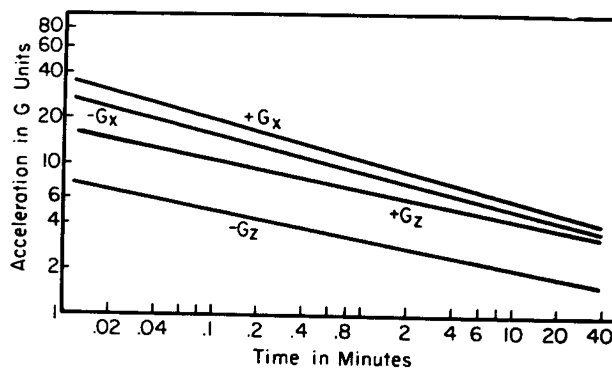


FIGURE 4. Average acceleration tolerances for positive acceleration ($+G_Z$), negative acceleration ($-G_Z$), transverse supine acceleration ($+G_X$), and transverse prone acceleration ($-G_X$).

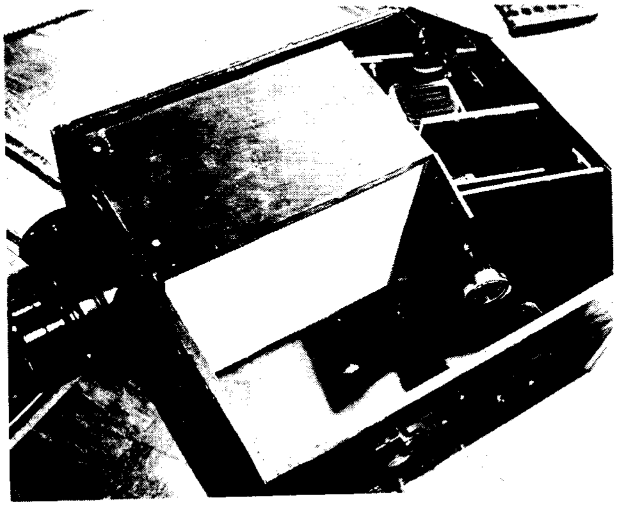
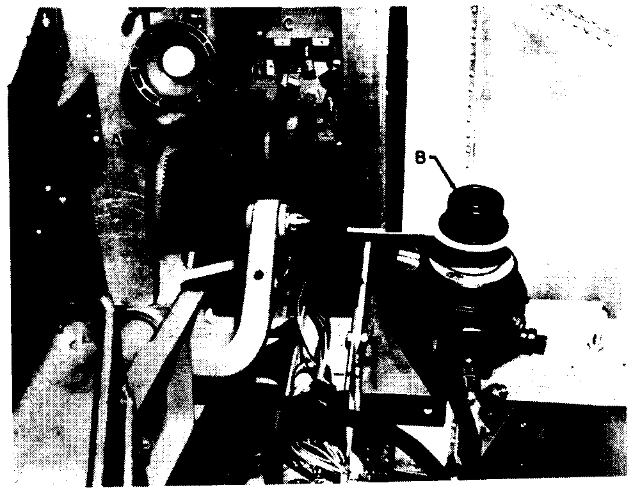


FIGURE 5. Stimulus Display Generator.



A. Mercury Type Control Handle
B. Oxygen Regulator
C. Visual Response Button

FIGURE 7. Pressure Breathing Oxygen Regulator

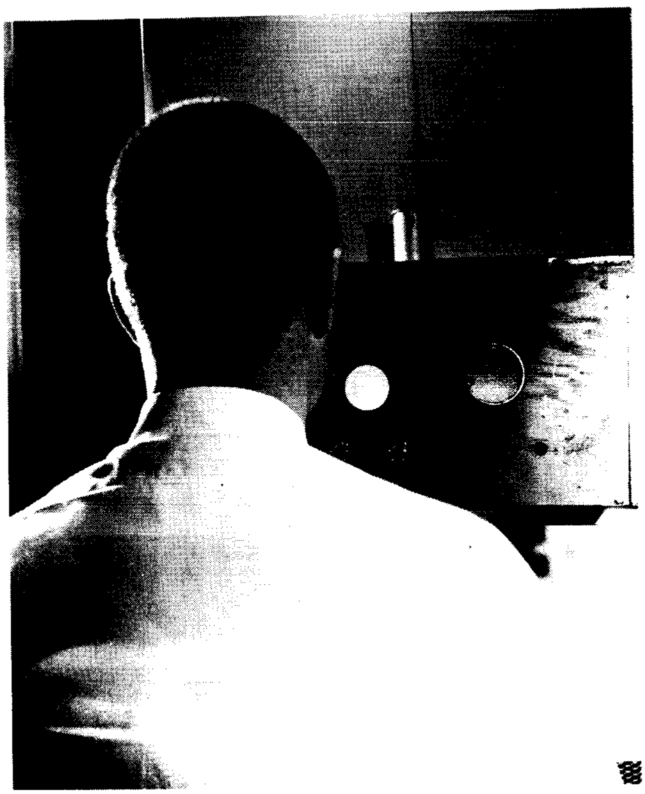


FIGURE 6. Subject shown viewing the stimulus display generator.

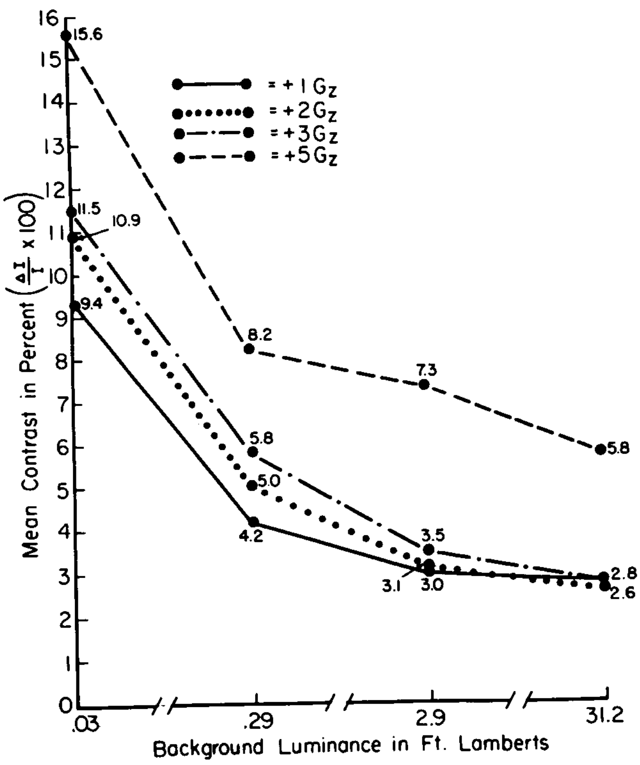


FIGURE 8. Results of experiment showing the relationship between brightness discrimination threshold and background luminance for each of four levels of positive acceleration.

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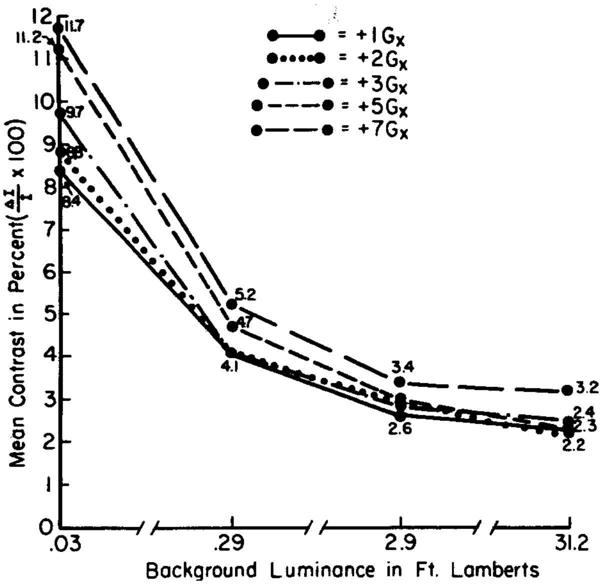


FIGURE 9. Results of experiment showing relationship between brightness discrimination threshold and background luminance for each of five levels of transverse acceleration.

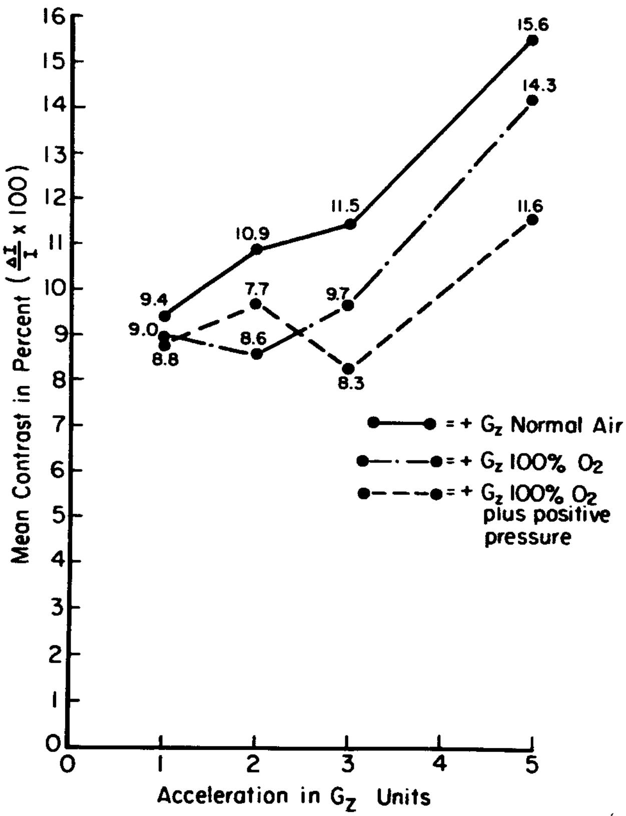


FIGURE 11a. Comparison of the effects of breathing normal air, 100% oxygen, and 100% oxygen plus positive pressure. The comparison is in terms of mean brightness contrast requirements during exposure to three positive accleration levels.

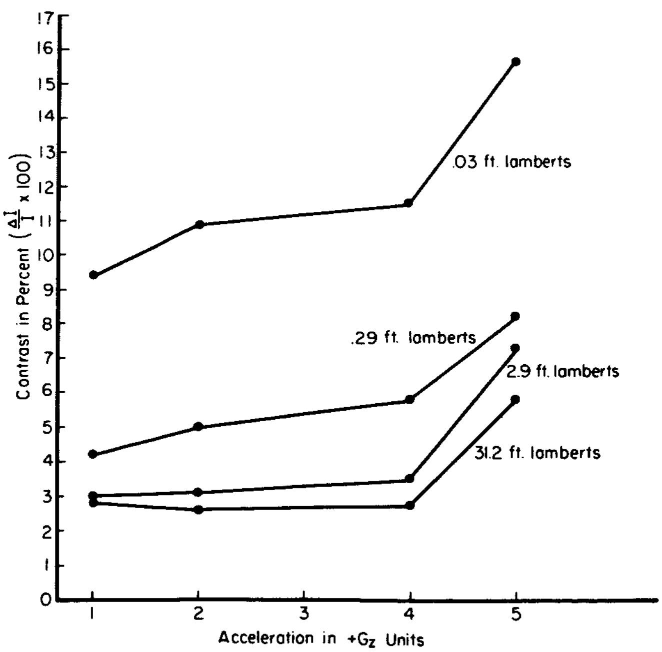


FIGURE 10. Effects of positive acceleration (+G_Z) on brightness discrimination thresholds for perceiving an achromatic circular target against each of four background luminances.

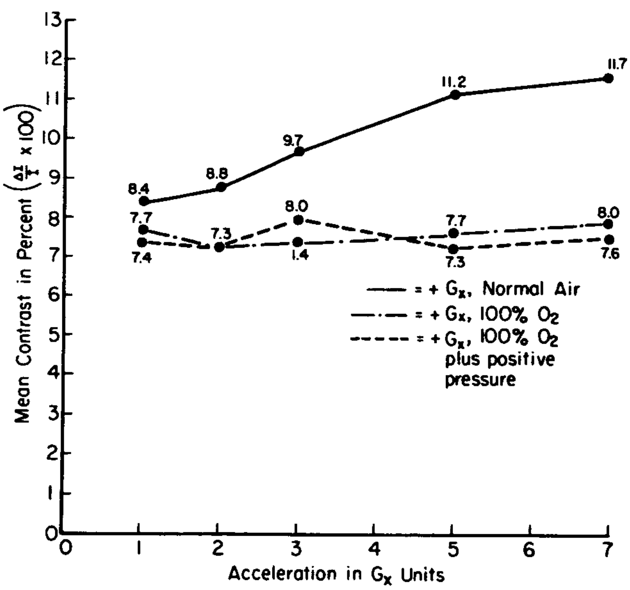


FIGURE 11b. Comparison of the effects of breathing normal air, 100% oxygen, and 100% oxygen plus positive pressure. The comparison is in terms of mean brightness contrast requirements during exposure to three transverse acceleration levels.

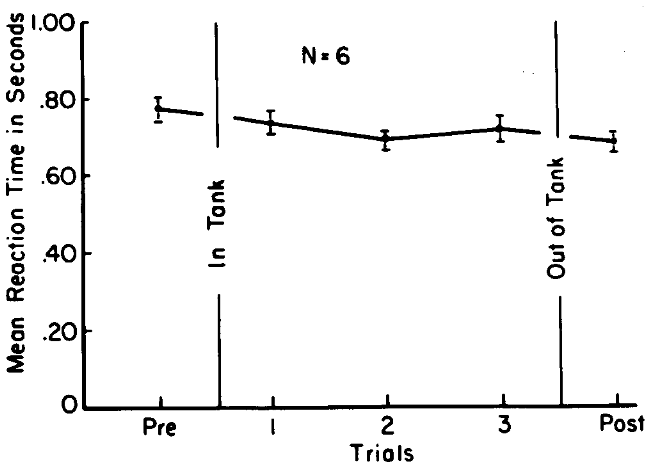


FIGURE 12. Discrimination under static and static-immersed conditions.

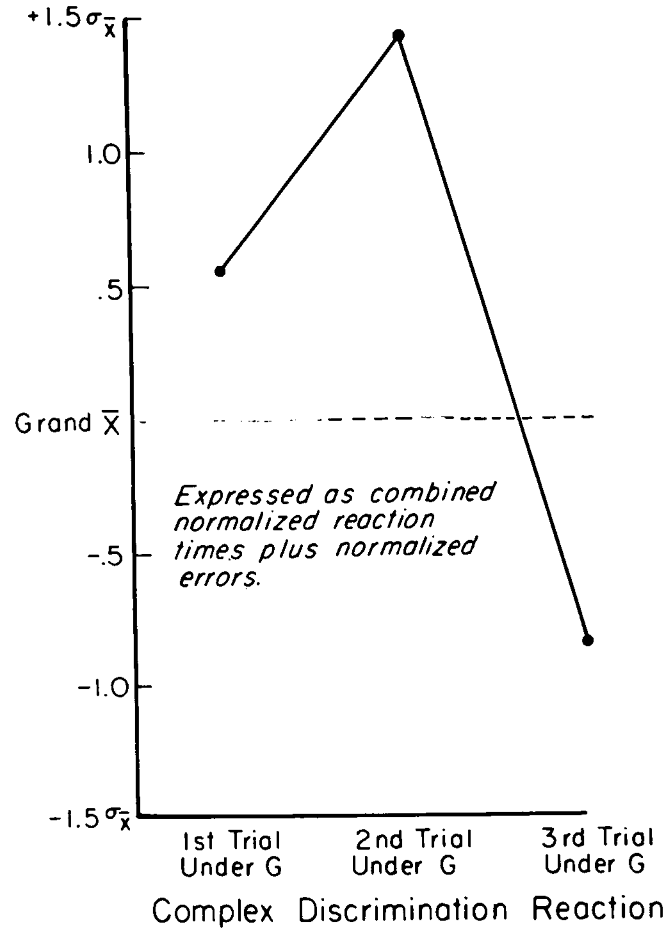


FIGURE 14. Discrimination reaction time performance during exposure to 6 G_x for 5 minutes per run.

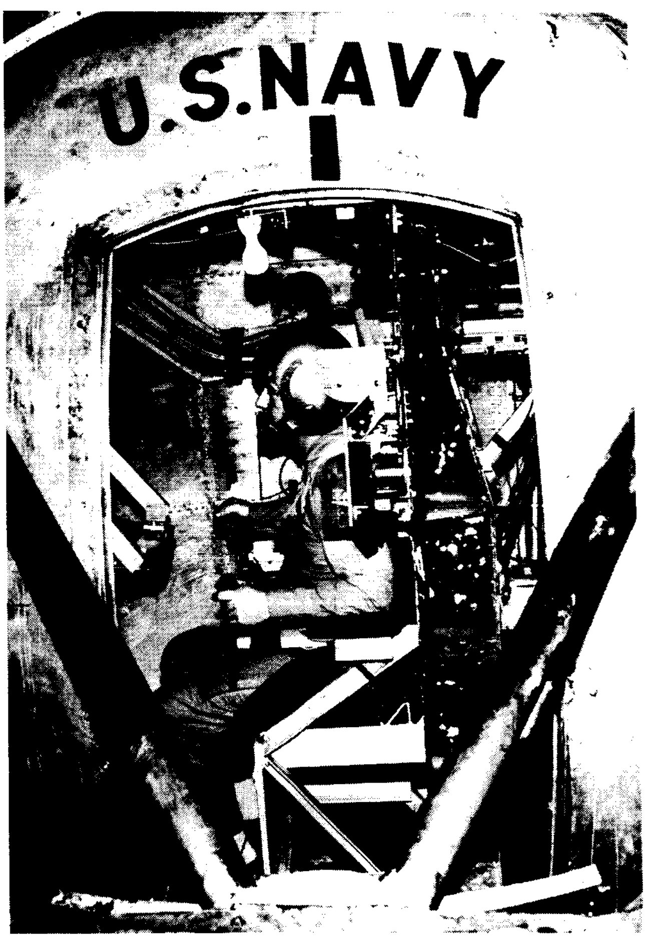


FIGURE 13. Centrifuge installation used in study of discrimination reaction time during exposure to acceleration. The subject responds continuously to each of four randomly presented lights by operating 4 small buttons on his right-hand control stick.

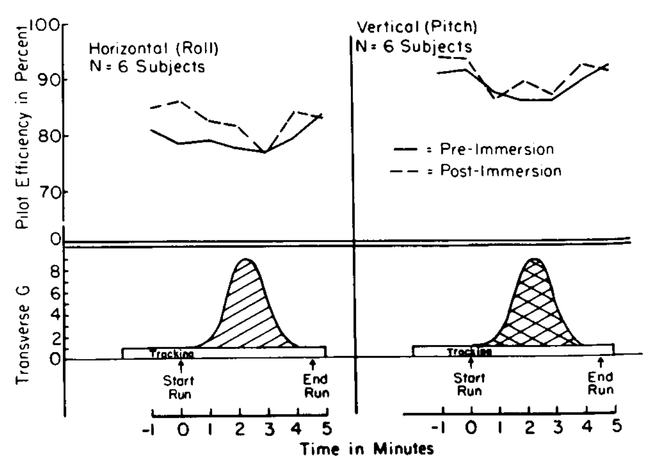


FIGURE 15. Mean pilot efficiency scores in tracking pitch and roll components during exposure to a transverse G reentry acceleration profile.

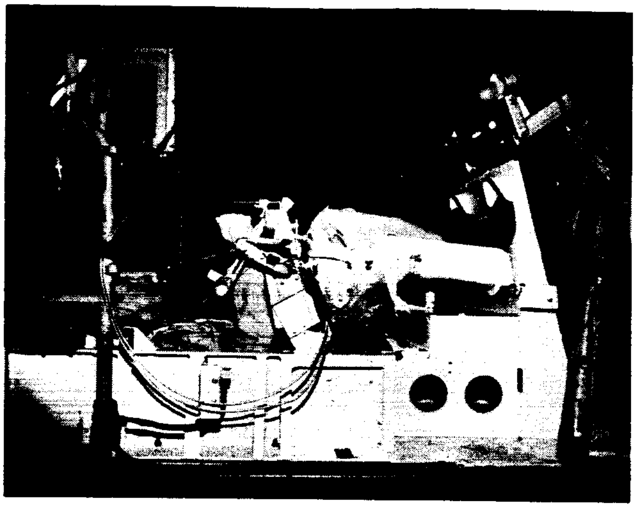


FIGURE 16. Subject positioned in contour couch, suspended from the centrifuge arm, and operating a control device during a tracking trial.

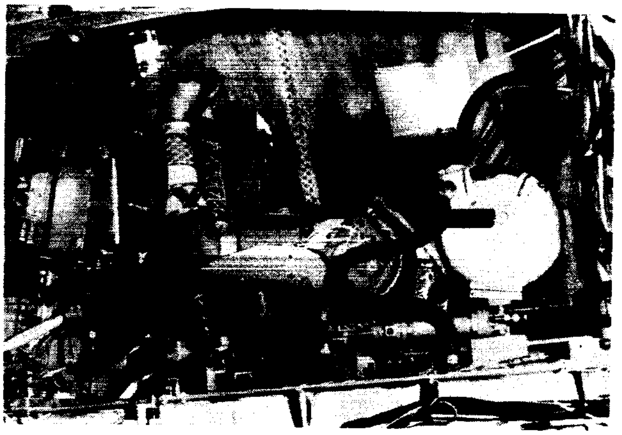


FIGURE 18. Pilot in advanced G-protection system, developed by NASA and tested at the AMAL Human Centrifuge. This system was designed to provide protection for $+G_x$ $-G_x$ and $+G_z$ accelerations.

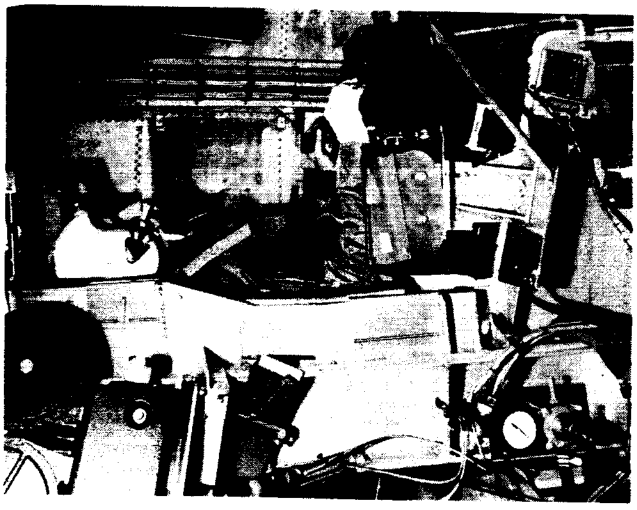


FIGURE 17. Pilot restrained in contour couch, with associated shoulder, arm, head, and face restraints performing a tracking task in the AMAL Centrifuge.

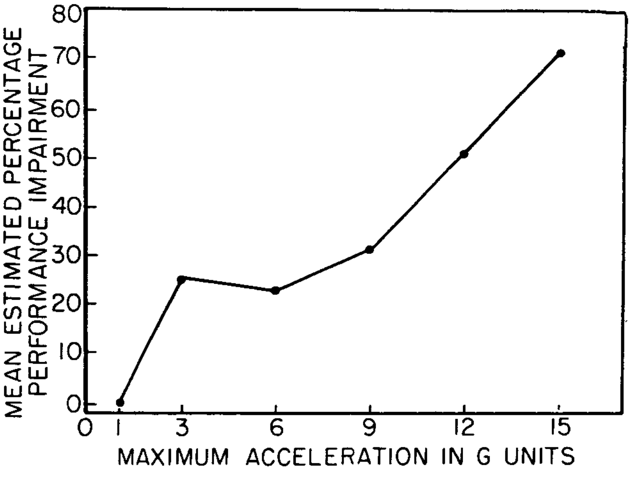


FIGURE 19. Average estimated performance decrements by pilots who performed complex launch and insertion maneuvers through peak accelerations of 1, 3, 6, 9, 12, and 15 G_x.

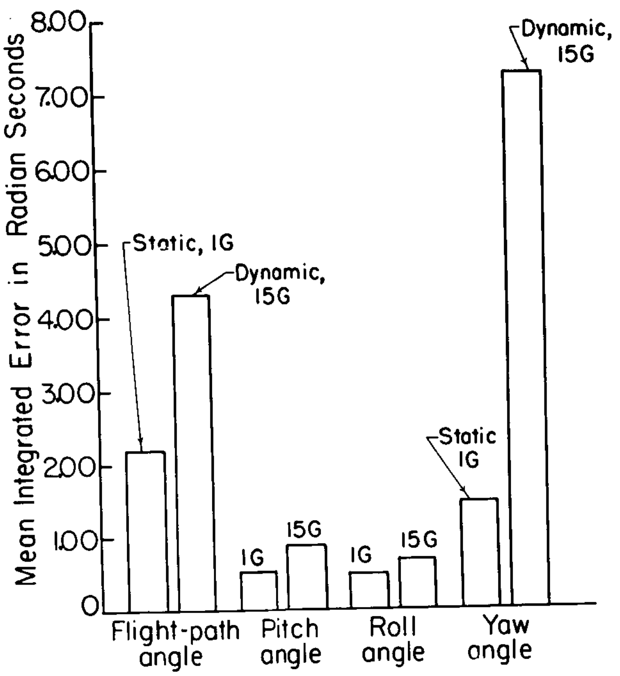


FIGURE 20. Pilot error performance on each of four task components during exposures to static (1G) and dynamic (15G) acceleration conditions.

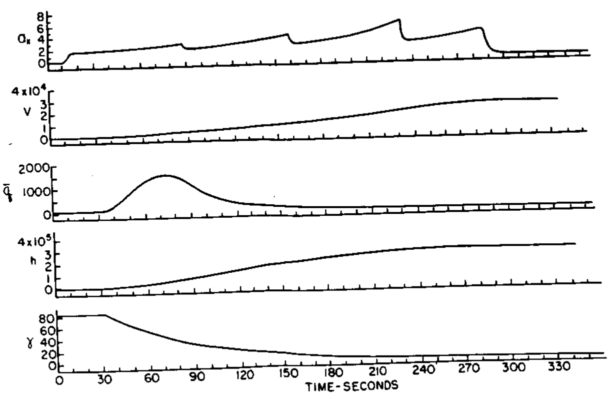


FIGURE 21. Acceleration profile used to simulate a 4-stage launch vehicle on the AMAL Human Centrifuge.

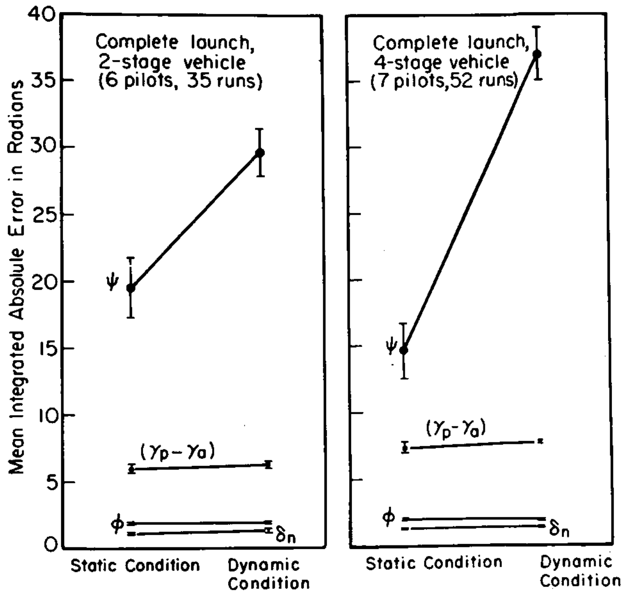


FIGURE 22. Performance scores for pilots performing a control task during the launch to insertion phases of a proposed boost four-stage vehicle.

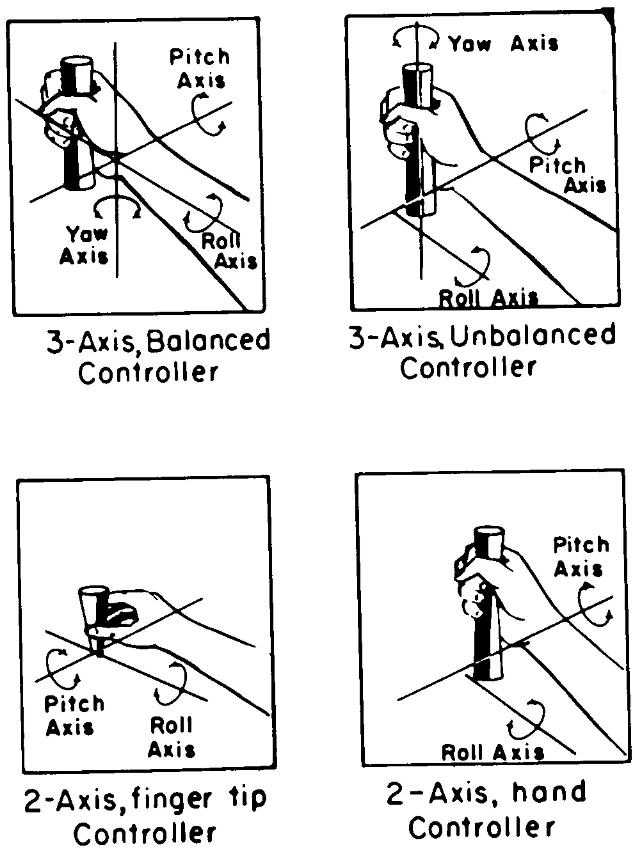


FIGURE 23. Four types of right-hand side arm controllers used in high-G sustained acceleration studies on the Human Centrifuge.

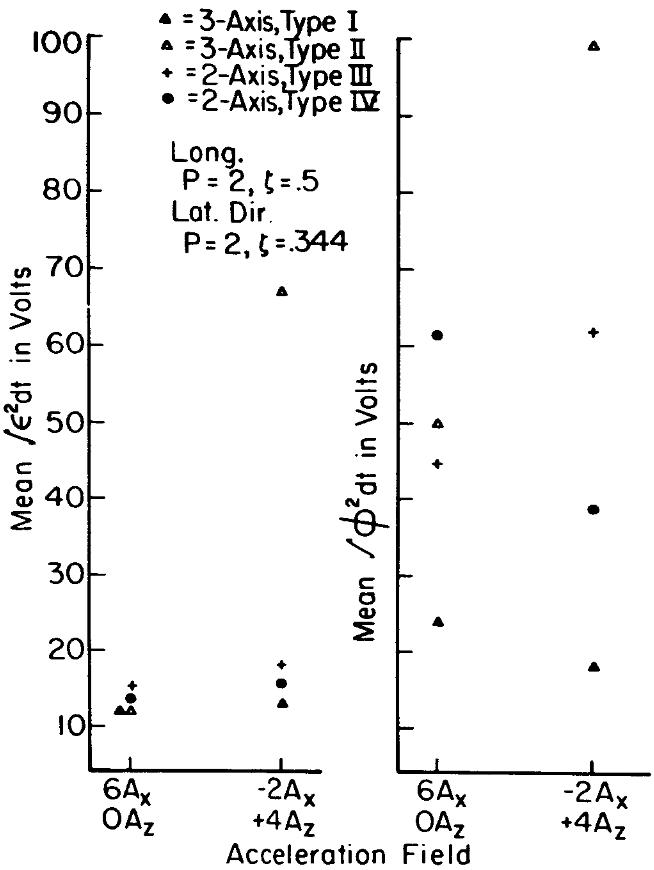


FIGURE 24. Mean error scores for pitch error and for roll error components of a tracking task in which the same pilots flew the same problem in each of 2 G-fields using each of four side-arm controllers.

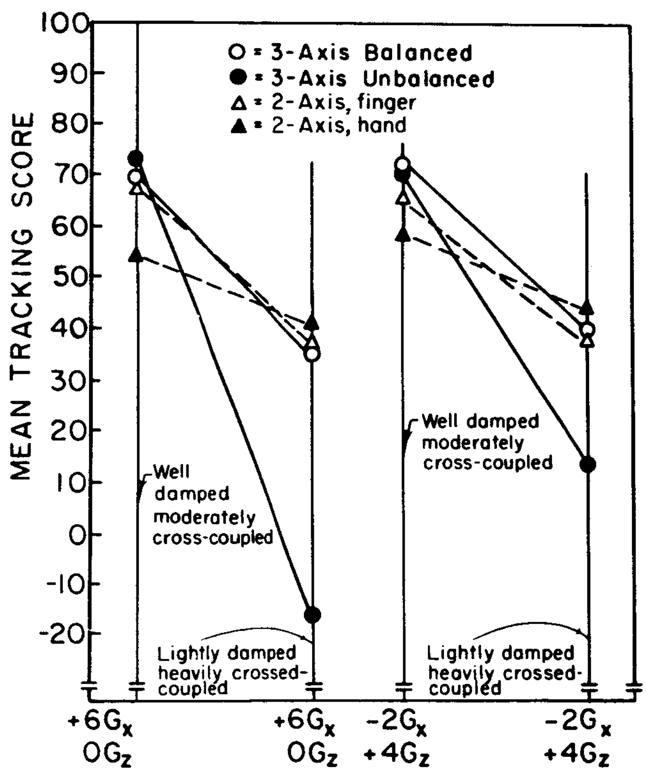


FIGURE 25. Mean tracking efficiency scores for pilots who performed the same tracking task with each of 4 different types of side-arm controllers within given acceleration fields.

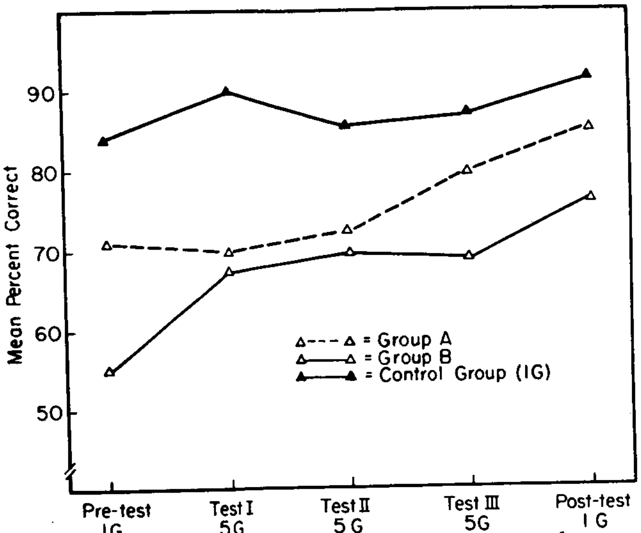


FIGURE 26. Performance of three groups of subjects on a 4-back running matching memory test. Group A was a sample of students from Rutgers University. Group B was a sample from AMAL, and Group C was a control group which performed the task only under static (IG) conditions.

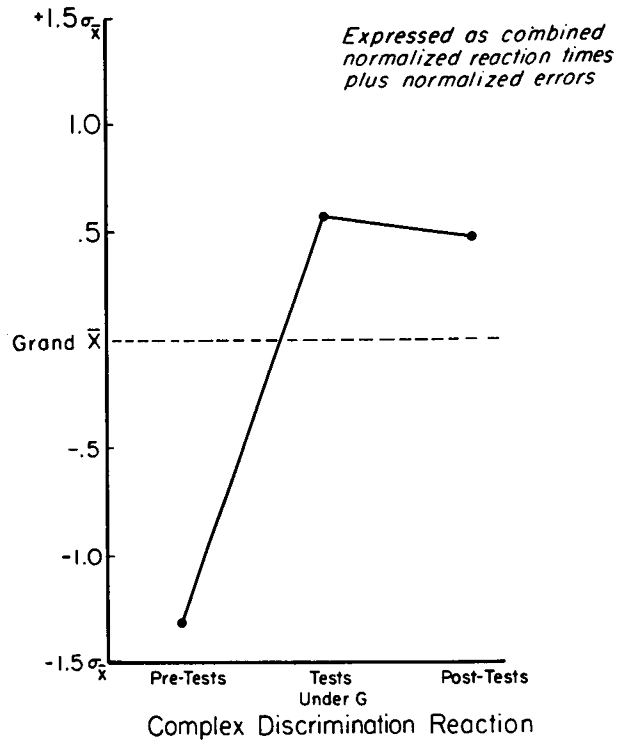


FIGURE 27. Results of administering a complex discrimination reaction time task before, during, and following exposure to 6 G_X. for 5 minutes per run. In order to account for both error and time decrement, reaction times and errors were normalized and then added in this experiment.

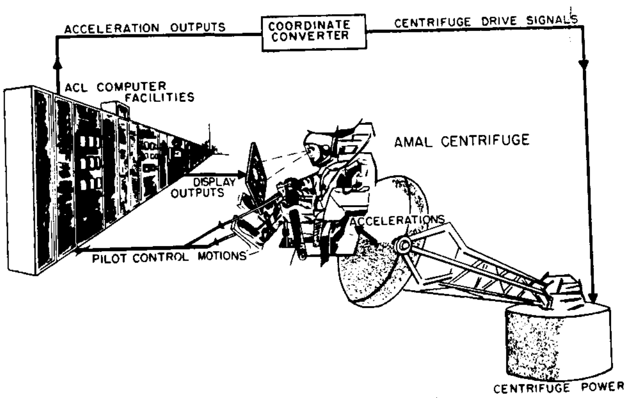


FIGURE 28. The centrifuge/computer interface during open-loop acceleration command (solid lines) and closed-loop panel display (open line).

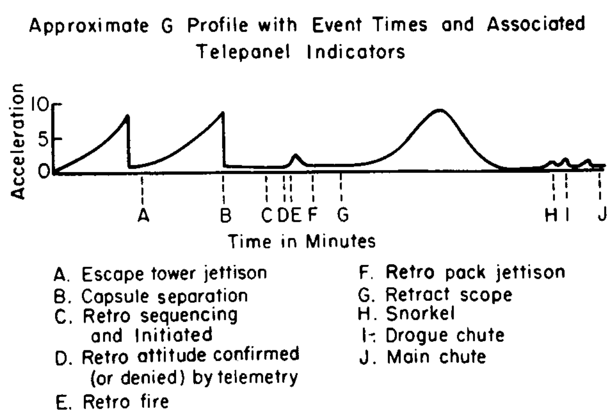
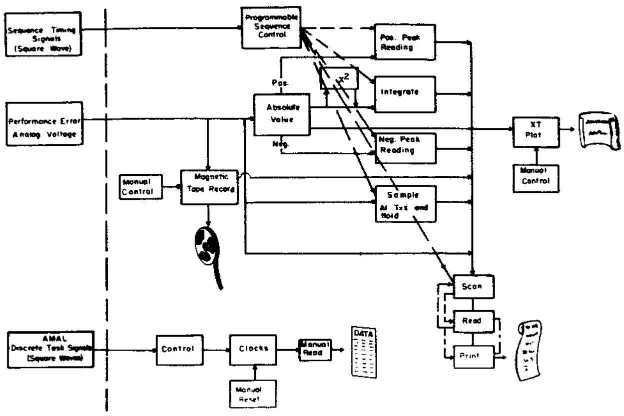


FIGURE 29

FIGURE 30 EPL Data Reduction Facility – Bldg. No. 85



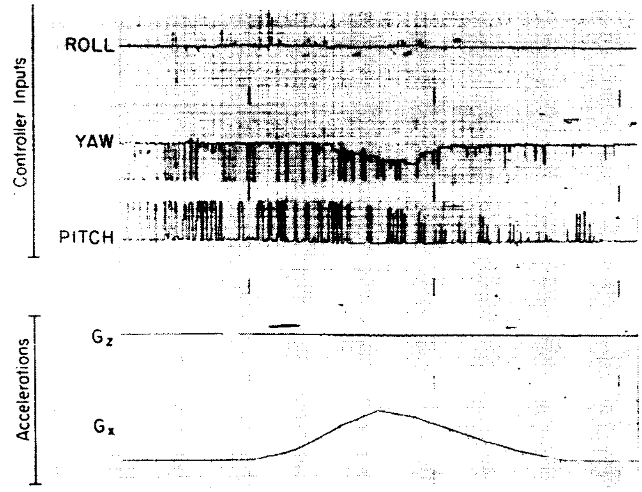


FIGURE 33 Inadvertant Control Input in the Yaw Axis

FIGURE 31. Externally mounted control panel.

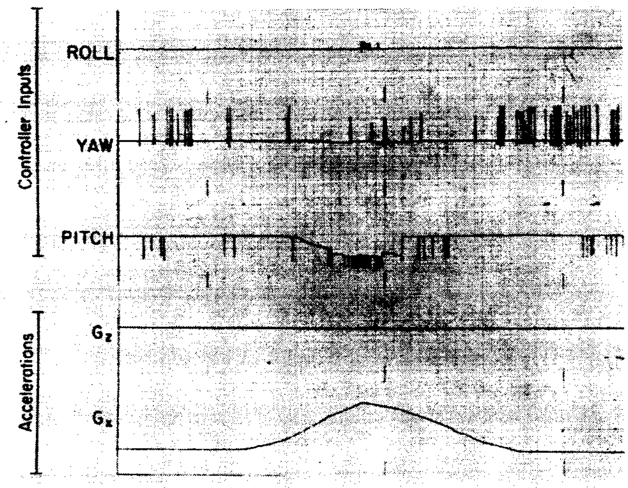


FIGURE 34 Inadvertant Control Input in the Pitch Axis

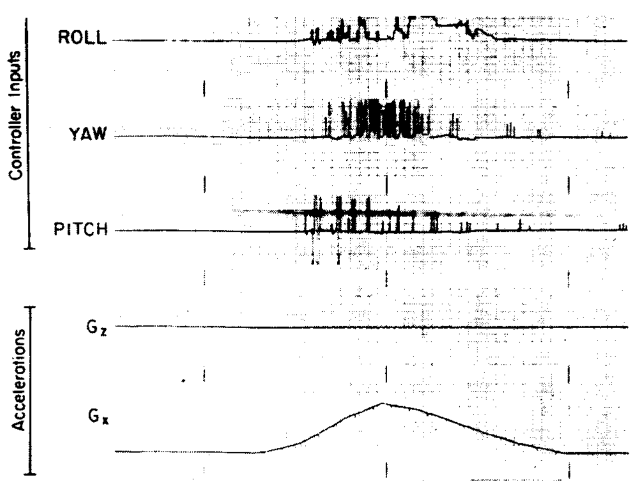


FIGURE 32 Inadvertant Control Input in the Roll Axis

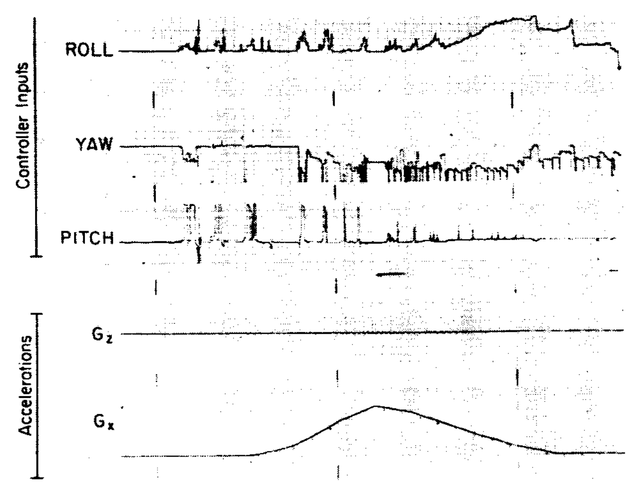


FIGURE 35 Simultaneous Inadvertant Inputs in the Roll and Yaw Axes

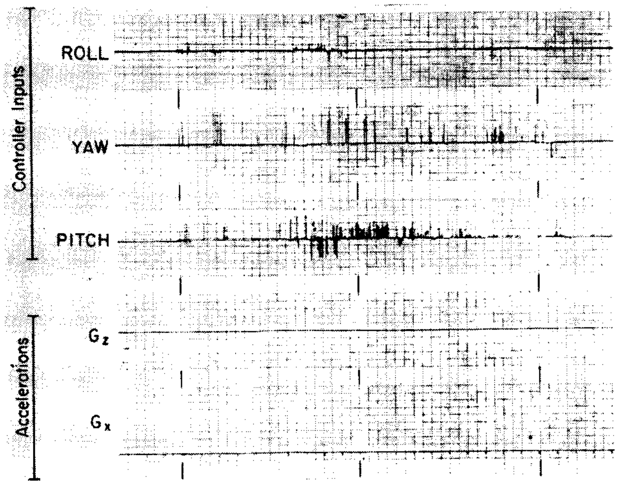


FIGURE 36 Sample Performance Under Static Conditions

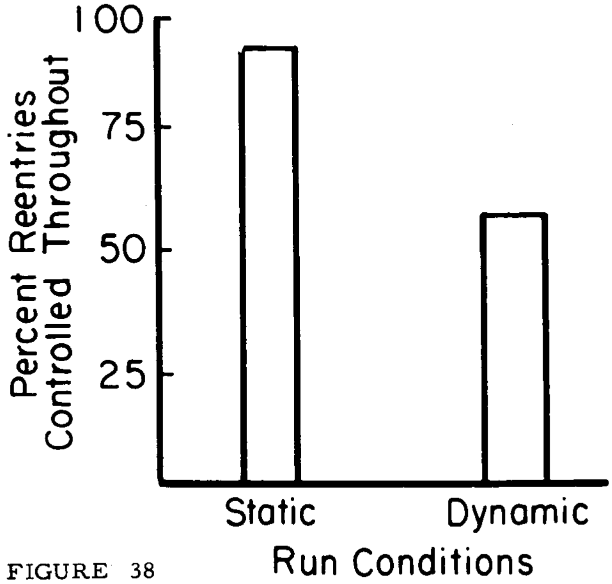


FIGURE 38

Reentry Control Under Static and Dynamic Conditions

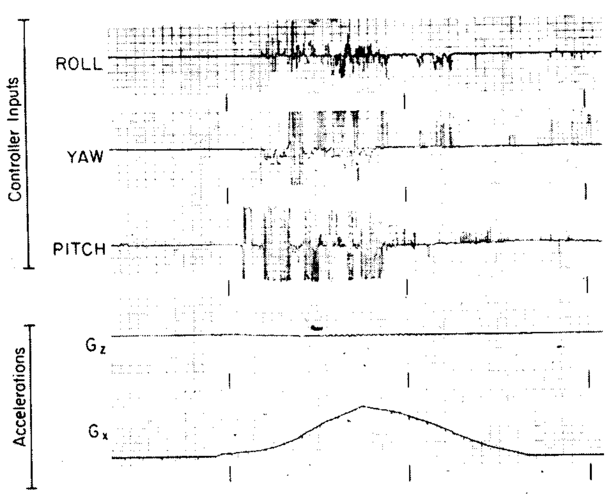
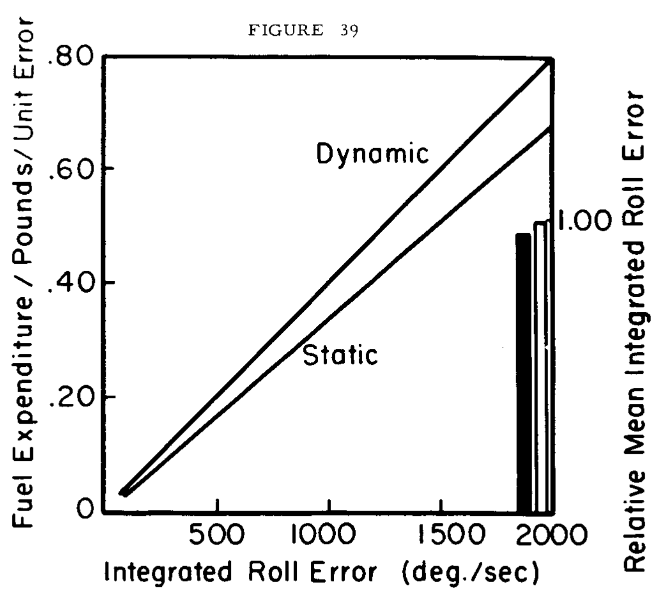


FIGURE 37 Performance of the Same Pilot Under Dynamic Conditions

FIGURE 39



Fuel Utilization as a Function of Error Magnitude and Acceleration

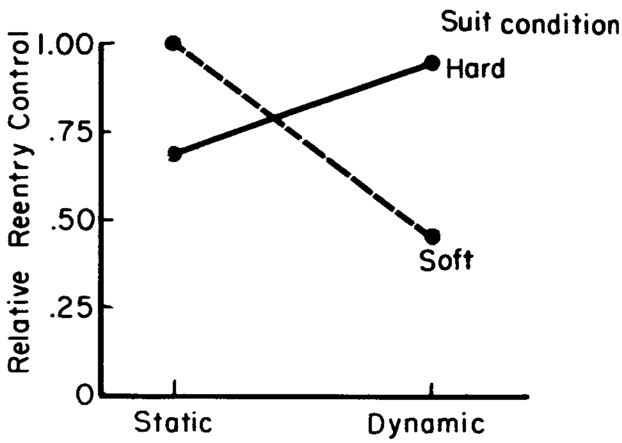
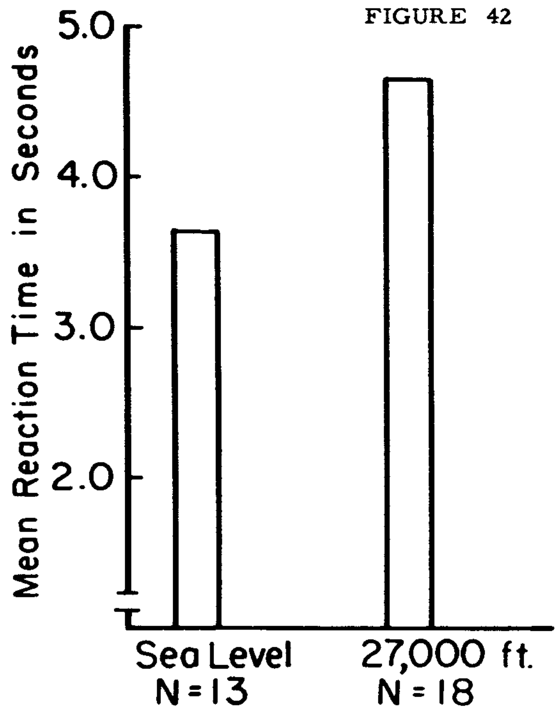


FIGURE 40 Run Condition

Relative Reentry Control as a Function of Suit Pressurization and Acceleration

FIGURE 42



Cabin Pressurization

Telepanel Response Time as a Function of Cabin Pressure

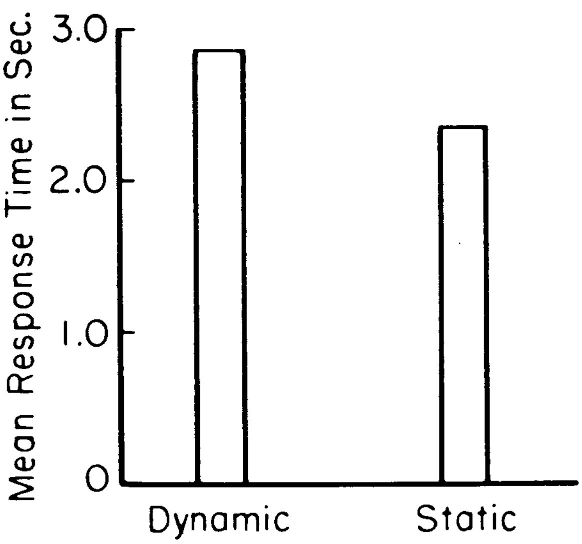


FIGURE 41 Run Condition

Telepanel Response Time Under Static and Dynamic Conditions

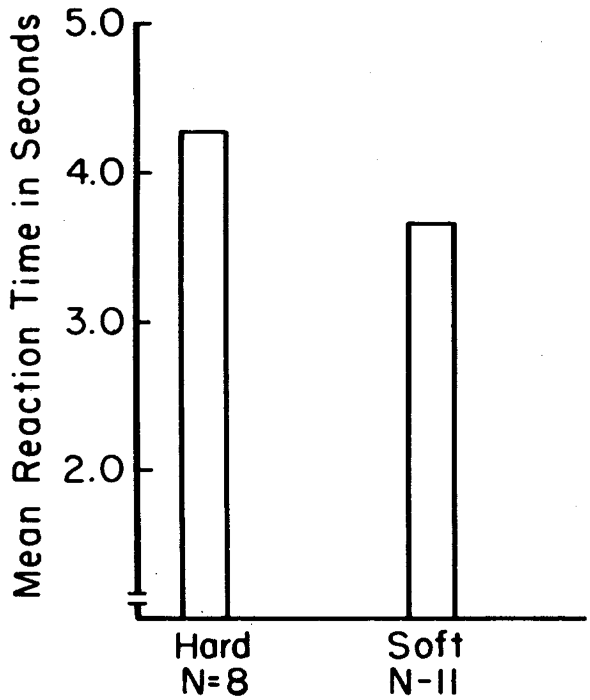


FIGURE 43

Suit Pressurization

Telepanel Response Time as a Function of Suit Pressure