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Influence of Sustained Accelerations on Certain Pilot-Performance Capabilities

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S PACE missions are being planned in which the pilot is a primary element in the control system of the vehicle. If it is assumed that the pilot will also control the space vehicle in the atmosphere entry maneuver, certain fundamental questions must be answered relative to the influence of acceleration forces on the pilot. Among these questions are: (1) How should the pilot be positioned in the vehicle to best withstand the applied g load? (2) What are the maximum periods of time a pilot can tolerate various selected levels of acceleration force while performing his control function? (3) What are the maximum rates of onset of the acceleration force to which the pilot should be subjected? For a given vehicle and mission profile, it would be desirable to evaluate the specific reentry piloting task in the precise acceleration-stress environment. In general, however, preliminary answers to the questions posed must be obtained well before the spacecraft is clearly defined, and, hence, well before a specific reentry evaluation is possible.

One method of obtaining preliminary evidence is to place the pilot in the desired acceleration-force environment until he fails physically; the limit point would thus be defined. A second approach would be to place the pilot in the desired acceleration-force environment and require him to perform a task which might not match the specific reentry piloting task, but would be sufficiently difficult to increase the pilot's sensitivity to acceleration as measured by a sudden decline in his performance. If the selected task were sufficiently difficult, the pilot's

performance would deteriorate well before he reached any physical limit.

The National Aeronautics and Space Administration has a general program to study the effects of acceleration on the pilot of a space vehicle. As part of this research program, a rather extensive investigation of the effects of acceleration on pilot performance and pilot physiology was conducted on the Johnsville human centrifuge by Ames Research Center. Though the program was very general and was not directed at any specific vehicle, certain results have been selected, and will be used in the manner just discussed, in an attempt to answer the questions concerning pilot's limitations. That is, the approach was to provide the subject test pilots with a very difficult control task, which although probably not representative of an actual reentry piloting task, certainly produced the desired effects of causing a measurable deterioration in pilot performance well before a physical tolerance limit was reached.

In this paper, the vernacular of the test pilot has been used to describe the direction of the applied acceleration force. The terms "eyeballs in" (EBI), "eyeballs out" (EBO), and "eyeballs down" (EBD) correspond to acceleration fields A_X, $-A_X$ and A_N, respectively; A_X, $-A_X$ and A_N refer to the direction of acceleration forces measured in the conventional airplane body-axis coordinate system.

APPARATUS

The centrifuge at the Aviation Medical Acceleration Laboratory, Naval Air Development Center, Johnsville, Pa., was used in this research program to investigate the pilot control problems associated with the atmosphere reentry of

space vehicles. For a fairly detailed description of the centrifuge, see references 1 and 2.

Obviously, the ability of the pilot to function in a sustained high-acceleration force field and his tolerance to acceleration limits are critically dependent upon the quality of his restraint system. Thus to insure the maximum in pilot performance, a program was initiated to develop an integrated mobile pilot restraint system, and the system that evolved is described in detail in references 3 and 4. Certain basic concepts were incorporated which might be useful in the design of a restraint system for use in a space vehicle. Its advantages are that it can be donned easily and the pilot can quickly attach it to the basic support and release it. However, since a shirt-sleeve environment would be a desirable requirement in a flight vehicle, further simple modifications are necessary to enable the pilot to don it alone. This support and restraint system was designed primarily for simulator studies of flight vehicle control under varying conditions of acceleration stress. For this purpose, it has served well.

There are two main areas in which this current restraint system is untested, namely, impact accelerations and lateral transverse forces, either sustained or impact. It is probable that the present restraint, with certain modifications to the bladder system, will adequately protect the pilot against impact acceleration forces.

An earlier pilot restraint system, developed by the Ames Research Center and described in reference 5, utilized a moulded couch arrangement similar to the Mercury system but with what is regarded as an improved anterior restraint system to provide support for the eyeballs-out (EBO) g-field direction. The experience gained in using this restraint system contributed to the development of the present system.

For all the performance data presented in this paper, the pilot used a finger-operated two-axis side-arm controller and toe pedals. A description of the finger-operated side-arm controller and of the toe-pedal controls is given in reference 6.

To obtain a quantitative measure of pilot's performance, the pilot was required to track a randomly driven target, while flying the simulated entry vehicle. A cathode ray tube in the instrument panel displayed the tracking task.
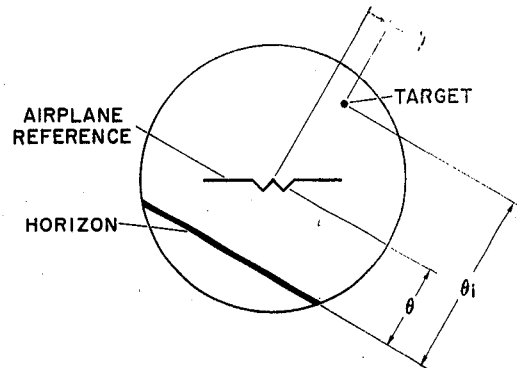

Fig. 1. Pilot's scope display.

The target on the scope was driven in the fashion shown in Figure 1. The task was to track the target driven, relative to the Earth's axes system, through the angles θ_i. The random signal that drove the target in the vertical plane (θ_i) was the sum of a set of four sine waves. The amplitude of the sine waves ranged between 1.17 and 0.316 centimeters, when displayed on the scope face, and the sine wave frequency ranged from 0.277 to 1.80 radians/sec. The initial phase angles for the various sine wave signals were completely random.

The target was not actively disturbed in azimuth (Ψ). However, the target was free to move in azimuth and an azimuth tracking error would occur if the heading of the tracker airplane deviated away from the original zero heading reference. The pilot's tracking error in the vertical plane was computed according to the following equation:

$$\epsilon_\theta = \theta_i - \theta$$

This particular tracking task was selected since previous experience[6] had shown it to be fairly realistic from the pilot's point of view. With the pilot flying the simulated entry vehicle

and performing the specified tracking task, it appeared that the pilot was operating at near his maximum work level. It is believed that if the pilot is forced to operate at near his maximum capability, changes in his performance, due to changes in the applied acceleration force, et cetera, are more easily discerned. In addition, the sum of four sine waves could be generated easily and had a frequency spectrum somewhat similar to gust disturbances.

Bank and pitch attitudes were displayed on the scope face in the same fashion as on the conventional gyro horizon indicator. The angle of attack, course heading, flight path angle, et cetera, were displayed on conventional dial indicators.

DATA ANALYSIS

The time history of the pilot's pitch tracking error was processed in a manner that gave a quantitative index of pilot performance. The purpose of the performance index was to facilitate the comparison of the tracking performance of numerous pilots operating in a variety of test conditions. Two different methods were used for processing the tracking error time histories. One method was used for analyzing the influence of sustained acceleration on pilot performance and a different technique was used to determine the effect of g onset rates on pilot performance.

The influence of sustained acceleration on pilot's tracking performance was analyzed on an analog computer which determined the root-mean-square error from the tracking data that had been preserved on magnetic tape. First, the noise present in the error signals from the taped record was reduced to an acceptable level. For this, a second-order filter with a natural frequency of 5 cps and damping ratio of 0.6 was used. The filtered signal was then squared and integrated. The integral of the error squared was passed through a three-second delay circuit and subtracted from the undelayed integral of the squared error. The square root of one-third of the difference was obtained giving a root-mean-square error for a continuously moving three-second interval. This error measure was

relatively sensitive to variations in pilot performance and did smooth the data somewhat, allowing the general nature of the tracking performance within a run to be evaluated. To facilitate comparison of the results for the various test conditions, an average of the rms error for the three-second interval was obtained by integration for successive 20-second periods. This allowed the average rms error to be determined for the specific intervals of interest for each test run. A mathematical description of these calculations is:

$$\text{rms error} = \int_{20n}^{20(n+1)} \sqrt{\frac{\int_{t-3}^{t} (\epsilon_\theta)^2 dt}{3}}$$

where ϵ_θ is the error signal and $n = 1, 2, 3, \ldots$ intervals to end of run. All the data for the acceleration portion of the runs were then adjusted to the average 1 g error.

In analyzing the influence of rate of onset of g on pilot performance, the mean squared tracking error was estimated over the duration of the onset period. This estimate was based on the radius of gyration under the error-time curve about the zero error axis. The function calculated is:

$$\text{rms error} = \sqrt{\frac{\int_0^t |\epsilon_\theta^3| dt}{\int_0^t |\epsilon_\theta| dt}}$$

As compared to the usual root-mean-square error, this estimate is more sensitive to large excursions in tracking error and less to small deviations. It is believed therefore that important effects due to rate of onset of g are brought out, and differences due to small random error are suppressed.

TEST CONDITIONS

The pilot flew the centrifuge as a closed-loop system; that is, for acceleration fields greater

than 1 g, the centrifuge was driven in response to the pilot control inputs in such a way that the actual linear accelerations varied in the same manner as the linear accelerations computed from the aircraft equations of motion. A detailed description of the closed-loop centrifuge operation is given in reference 7. The test setup was arranged so that the total g field impressed on the pilot consisted of two separate components; to a specified constant (biased) g field was added the computed perturbations in normal and side accelerations which resulted from the vehicle maneuvering about a given trim condition. The perturbations in side and normal accelerations were generally not greater than ±0.5 g. In this experiment, the aircraft equations of motion described five degrees of freedom with the vehicle forward velocity assumed to be constant.

The simulated entry vehicle response characteristics were representative of those for a winged configuration with a high lift to drag ratio and with stability augmentation to improve the controllability of the vehicle. When flying this simulated entry vehicle, the pilots judged its handling qualities to be near the satisfactory level. The airframe dynamics were selected so that the least experienced test pilots apparently required their maximum capability to perform the required tracking task in an elevated g field.

Prior to any high-g data runs, the pilots were conditioned to the effects of sustained accelerations and were familiarized with the piloting tasks and the centrifuge. For the most part, the pilots were not exposed to acceleration levels over 6 g during the familiarization period.

Prior to any centrifuge run, the pilots were given a fairly detailed briefing. They were instructed to perform the piloting task continuously from the beginning of the run, through the complete acceleration-profile time history, to the termination of the run. They were instructed to terminate the run at any time they felt a marked deterioration in their ability to fly the vehicle. The pilots were further instructed to terminate the run at any time they felt that a real physiological problem existed,

when physical discomfort reached a level that it precluded retaining effective control over the vehicle, or when anything of an untoward nature occurred. Specific medical instructions to the
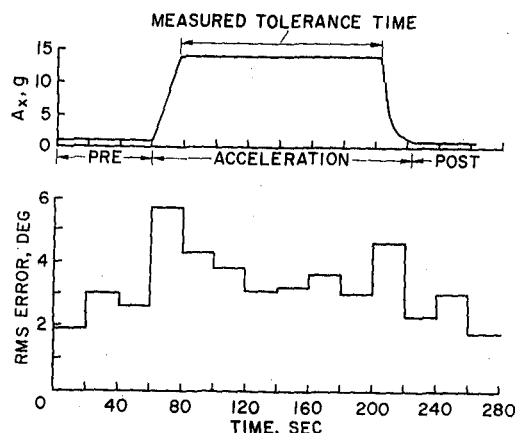

Fig. 2. Tolerance and performance run.

pilots were to terminate a run whenever there was a marked sudden loss of vision, whenever there was a marked disorientation or vertigo, or when there was a sudden onset of pain in the chest. The medical doctor and engineer monitoring the physiological and performance records could also terminate the runs at their discretion.

A qualitative measure of pilot performance was obtained by having each pilot give a numerical rating to the controllability of the simulated vehicle. The rating was based on a pilot-opinion rating schedule similar to that presented in reference 8. As noted previously, a quantitative measure of the pilot's performance was given by the tracking task.

The centrifuge runs began at the 6 g level and, in general, progressed at 2 g increments up to the maximum g level the pilot could tolerate.

DISCUSSION

Figure 2 shows a typical acceleration time history of a pilot-performance centrifuge run. As can be seen, the run was divided into three major segments. In that segment noted "pre-acceleration" the pilot was required to fly the simulated vehicle and track the randomly driven target for 1 minute in order to establish a base-

line on his tracking performance. The pilot continued to track the target during the onset of acceleration, while immersed in the g field, and during the post-acceleration period which ex-

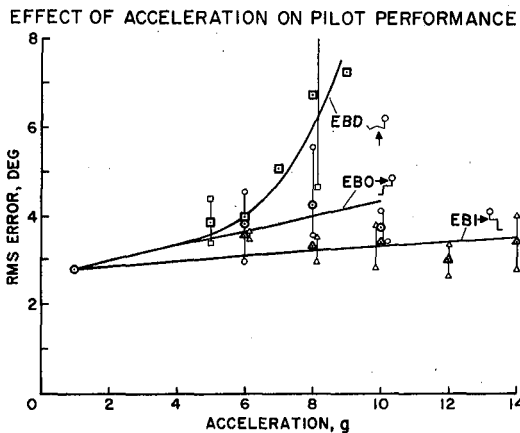EFFECT OF ACCELERATION ON PILOT PERFORMANCE

Fig. 3. Effect of acceleration on pilot performance.

tended 30 seconds after the decline of the acceleration. For most runs the rate of onset of acceleration was constant at 0.25 g per second, however, for this particular run the rate of onset of the g field was 0.75 g/sec. The rate of decline of acceleration was fairly rapid and followed an exponential curve. It should be noted that the tolerance time was measured over that interval wherein the acceleration was within about 10 per cent of the desired value.

A measure of the pilot's ability to track is shown in the second trace in Figure 2. The pilot's tracking performance has been presented in bar graph form with each bar representing, essentially, the tracking root-mean-square error, averaged over that particular 20-second interval. It should be pointed out that in this particular run a 14 g EBI acceleration force field was impressed on the test pilot subject. This was the highest acceleration stress impressed on the pilots during this research program. This particular run was used for illustrative purposes, not only because it was the severest acceleration-stress run, but because the variation in pilot tracking performance with time was generally typical of that occurring in the majority of the pilot-performance centrifuge runs.

A fairly strong point apparent from the tracking trace is the fairly marked deterioration in pilot tracking ability during and immediately after the onset of acceleration. This effect was most marked for the eyeballs-out and eyeballs-in runs. This deterioration in tracking is apparently due, for the most part, to pilot vertigo, the vertigo sensations being caused by the angular rotations of the centrifuge gondola as the centrifuge was brought up to the desired operating speed. Following the onset of the acceleration, the pilot tracking performance improved rapidly, stabilizing out at a reasonably constant level. The pilot's tracking ability improved significantly following the decline of the acceleration force field. During the post-acceleration period, the pilot's tracking performance was generally worse than during the preacceleration portion of the run by an rms error of from $1/2°$ to $3/4°$

In Figure 3, where the effect of g magnitude on pilot tracking performance is shown, the performance is measured during the latter portion of the sustained g run, after the initial vertigo effects have subsided.

The data in Figure 3 have been presented to help answer the question of how the pilot should be positioned in the vehicle. In this figure, rms tracking error data have been plotted as a function of the magnitude of the acceleration force field impressed upon the test subject for the "eyeballs-out," "eyeballs-in," and "eyeballs-down" g field directions. For the most part, the data points presented represent the average tracking performance of four test pilots. The maximum scatter in the data is shown by the vertical line drawn through the averaged data point. From this figure it can be seen that there was a very moderate drop in pilot tracking ability with increases in the magnitude of the g field for the EBI g field direction. At 14 g EBI, the pilot could momentarily control the vehicle quite effectively; however, his tracking performance was lower than that in the earth's 1 g field. The tentative interpretation of the pilot tracking capabilities was that, with the given vehicle dynamics, the pilot could adequately control the

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aircraft while immersed in an EBI acceleration field of 14 g.

Based on the limited amount of data obtained during this centrifuge investigation, it is apparent that at the 10 g level, there is a small reduction in tracking performance in the EBO acceleration field as compared to the EBI field. The reasons for this tracking performance difference will be discussed in a subsequent section of this paper.

The third worthwhile point shown in Figure 3 is that there was a marked deterioration in the measured performance above 7 g for the EBD direction. At the 7 g level, the subject's ability to see was greatly reduced, and at the 8 and 9 g levels, the subjects were on the verge of unconsciousness. One of the major objectives of this program was to determine the maximum acceleration level beyond which the pilot could not effectively control the vehicle manually. The abrupt falling off of the pilot performance in a 7 to 8 g EBD field is a good demonstration of this point.

Certain pilot tracking performance data were obtained from an earlier centrifuge investigation and were reported in reference 6. In that investigation, the maximum acceleration stress was 6 g, and data were obtained for the EBI, EBO, and EBD accelerations for well-damped and lightly damped vehicle motions. The well-damped case corresponds to a fairly easy control task and the lightly damped case corresponds to a fairly difficult control task. The conclusions drawn from reference 6 indicated the pilot tracking score was independent of the direction of the applied acceleration investigated. The pilot tracking score deteriorated markedly at accelerations greater than 4 g for a lightly damped dynamic situation. Finally, it appeared that the more difficult control task greatly magnifies any deficiencies in the pilot's performance. For the present investigation the simulated vehicle motions were well damped and the general trend of the plotted data points were compared with appropriate tracking data of reference 6. The general trend of the data obtained in the present study would tend to con-

firm the results of reference 6. However, a direct comparison of the two sets of data is not possible since the method of computing pilot tracking error was different in the two studies.
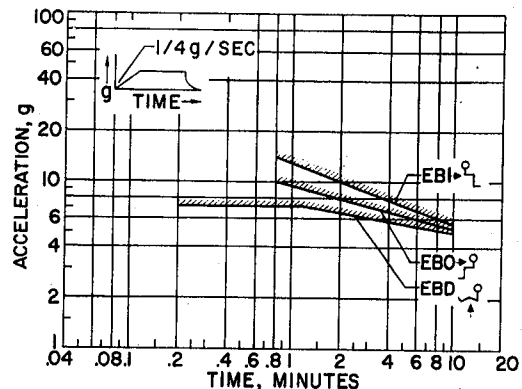

Fig. 4. Pilot performance boundaries.

Figure 4 presents the pilot-performance boundaries established by the Ames investigation. The term "pilot-performance boundaries" is used since these curves are based on the longest time the pilots could manually fly the vehicle in a given g field with no marked deterioration in their performance. However, these boundaries essentially define the longest periods of time a test pilot, preconditioned to the effects of acceleration and suitably restrained, would voluntarily endure a given sustained g level and perform any kind of a control task. The pilot's posture upon which these boundaries are based is shown in the figure. The normal seated position was used for eyeballs-in and eyeballs-out runs. For the eyeballs-down runs, the pilot's lower legs were elevated in order to minimize the pain and reduce the hydrostatic pressure in the pilot's feet. An anti-g garment was worn by the test pilot during the eyeballs-down runs.

A pilot can perform longer with the acceleration forces applied in an eyeballs-in or eyeballs-out direction than in eyeballs-down direction which agrees with a well-established conclusion. The limit boundaries also indicate that for a given acceleration force, the pilot can perform longer in an eyeballs-in than in an eyeballs-out

g field. From the Ames tests it was documented that the pilot's respiratory efficiency was greater in the eyeballs-out g field as compared with that in the eyeballs-in g field. However, an over-
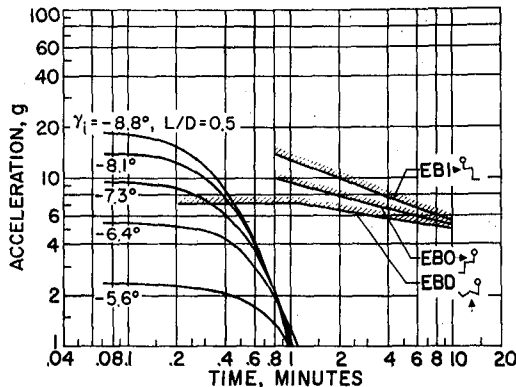

Fig. 5. Comparison of pilot performance limits with accelerations during entry.

riding point was that the pilot's visual problems were greater for the eyeballs-out g field. In the eyeballs-out runs, watering of the pilot's eyes could obscure the pilot's vision to the extent that he could no longer see the disturbed target clearly. The fact that the eyeballs-out boundary lies below the eyeballs-in boundary, and that the pilot's tracking was reduced somewhat when exposed to an EBO acceleration as compared to EBI acceleration seems to be a direct consequence of this visual problem.

It appears that a pilot could not control the vehicle manually for any extended period of time at acceleration levels in excess of 7 to 8 g eyeballs down. The cut-off boundary for the eyeballs-out or eyeballs-in g field direction was not determined. It appeared from this investigation that a well-trained pilot could still do a fair job of tracking the target between the 12 and 14 g level for the eyeballs-in g field direction. However, from Figure 3, it is seen that his tracking performance at 14 g was lower than that of his baseline tracking performance in the earth's 1 g field. Medical opinion was that it would be inadvisable to expose a pilot to g levels greater than 14 if the present pilot restraint system is used.

In Figure 5, the acceleration levels and period of time these acceleration levels must be sustained during entry into the earth's atmosphere beginning at parabolic velocities are compared with the pilot performance limit boundaries. These curves are drawn for initial entry angles γ_i ranging from $-5.6°$ to $-8.8°$ for a vehicle with $L/D=0.5$. It should be noted that these curves do not represent a time history. Perhaps the best way to explain these curves is to give an example. Given $\gamma_i=-8.1°$, the vehicle will sustain an acceleration force equal
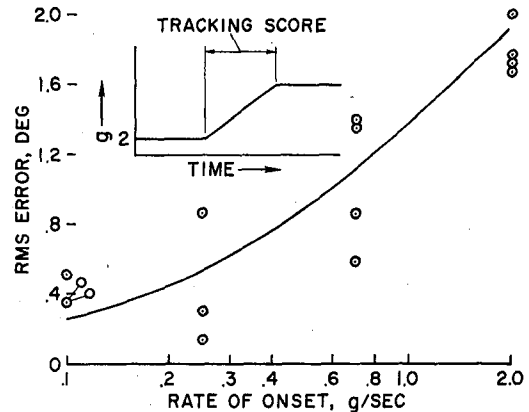

Fig. 6. Effect of rate of onset of g on pilot performance.

to or greater than 10 g for 0.35 minute. In comparing these curves with the pilot-performance boundaries, it would appear that the pilot could, if properly positioned, perform and tolerate the acceleration levels expected during an atmosphere entry with the initial entry angle of $-8.1°$. With an entry angle of $-8.8°$ there may be some question as to whether the pilot could physically tolerate the expected acceleration levels. The applicability of these tolerance boundaries to the case wherein the pilot is in a weightless condition for an extended period of time immediately prior to encountering a high sustained acceleration force is, of course, unknown at this time.

In Figure 6, data are presented showing the effect of rate of onset of acceleration on pilot performance. Rate-of-onset values of 0.1 g, 0.25 g, 0.75 g, and 2 g per second were in-

vestigated. The acceleration profiles to which the test pilot subjects were exposed are shown in the upper left of Figure 6. The baseline tracking ability of the pilot was measured by having the pilot track the randomly driven target for one minute in a 2 g force field. This was followed by the onset of the acceleration force up to an acceleration level of 5 or 8 g. Pilot vertigo, caused by the angular motions of the gondola as the centrifuge was brought up to the desired operating speed, was minimized by initiating the acceleration ramp from the 2 g level. The tracking data were measured during the interval from the beginning of the ramp to the end of the ramp. The data presented were gathered for both the eyeballs-out and eyeballs-in g field directions. (There were no systematic differences so the test conditions for the data points are not identified on the figure.)

The trend of the data is quite consistent and shows a fairly rapid decline in the pilot's ability to track for acceleration onset rates greater than 0.75 g per second. It might be noted that for a vehicle with L/D=0.5 the maximum acceleration onset rate encountered during a 10 g entry is approximately ½ g per second. The extent to which these data were influenced by pilot vertigo caused by the angular motion of the centrifuge gondola is unknown. In the opinion of the test pilot subjects, the vertigo effects on the pilot's ability to track were nominal for this phase of the investigation.

SUMMARY

An investigation was conducted by the Ames Research Center to assess effects of acceleration on pilot performance and on pilot physiology. This program was conducted at the Aviation Medical Acceleration Laboratory, Naval Air Development Center, Johnsville, Pennsylvania. The experimental flight simulator consisted of the centrifuge operated under closed-loop control. A quantitative measure of pilot performance was obtained by having the test pilot subjects fly a simulated entry vehicle and track a randomly driven target displayed on the face of a cathode ray tube.

The results of the test indicated that a pilot

could adequately control the simulated entry vehicle while immersed in a 14 g "eyeballs-in" acceleration field for two minutes. There was evidence of a small reduction in pilot tracking performance with pilots operating in an "eyeballs-out" acceleration field as compared with the eyeballs-in g field direction, and, in addition, the pilots could perform longer with the acceleration force applied in an eyeballs-in direction. The pilot's respiratory efficiency was higher in the eyeballs-out g field than in the eyeballs-in g field. However, an overriding point was that the pilot's visual problems were greater in the eyeballs-out g field direction. Some data were gathered on the rate of onset of acceleration on pilot performance. The trend of the data was consistent and showed a fairly rapid decline in pilot's ability to track for acceleration onset rates greater than about ¾ g per second.

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