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THE EFFECTS OF CENTRIFUGE RADIUS ON THE PERFORMANCE OF ENTRY TASKS

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by
W.C. MIDDLETON AND W.J. WHITE

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FOREWORD

This study is part of a program concerned with quantitative demonstration of the feasibility and general effectiveness of a short-radius centrifuge in an orbiting laboratory. It was supported by the Crew Systems Division, Manned Spacecraft Center, Houston, Texas, with Mr. W. V. Judy, Space Medicine Branch, serving as technical monitor. Dr. W. J. White was the principal investigator for the Douglas Aircraft Company, Inc., Santa Monica, California. This report is cataloged by the Missile and Space Systems Division, Douglas Aircraft Company, Inc., as Report No. DAC-59274.

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SUMMARY

The purpose of this study was to measure the effect of the force environment produced by a short-radius centrifuge on the basic motor skills required during entry. Two groups of 5 subjects each performed discrete response and tracking tasks under static and dynamic conditions at two different centrifuge radii, 64 and 178 in. An acceleration profile representative of Apollo entry was used during all dynamic runs. The change in Coriolis force and force gradient, produced by the change from the short to the long radius, amounted to approximately 40% of the change in those forces that would be encountered by an astronaut in going from an onboard centrifuge with a radius of 64 in. to actual entry.

When the centrifuge was moving, the time required to reach a control at a representative distance increased by 0.09 sec over that required when the centrifuge was static; it increased by 0.1 sec on the short-radius compared with the long-radius centrifuge. This was a 22% increase in each case. Continuous tracking errors were 4 to 6% larger when the centrifuge was moving than when it was static; they were 12% larger on the short-radius than on the long-radius centrifuge. These changes in performance, resulting from changes in the force environment, were sufficiently small, compared with normal variations in flight control performance, that they should not invalidate the onboard centrifuge as an entry-test device.

Positive transfer of training was obtained in going from the short- to the long-radius centrifuge, but negative transfer was obtained in going from the long- to the short-radius centrifuge.

INTRODUCTION

The feasibility of including a short-radius centrifuge in a manned orbital laboratory is being studied from both engineering and biomedical points of view. Systems comparison and selection studies of the penalties for producing artificial gravity show that incorporation of a centrifuge in a laboratory is feasible and is an attractive alternative to space station rotation. A parallel series of biomedical studies is in progress to quantitatively determine the effectiveness of a short-radius centrifuge as a training and research device and as a cardiovascular countermeasure for null gravity (ref. 1).

A major problem considered in the design of a centrifuge is to arrive at an acceptable tradeoff between radius of rotation and angular velocity. The former determines the acceleration gradient across the man and his work area, while the latter defines the Coriolis force produced by movements of his arms or legs. Because neither gradient or Coriolis are experienced during nominal entry, the effects of these artifacts on human performance remains undetermined. For a ground-based centrifuge an acceptable tradeoff is found at radii between 30 and 60 ft., where the values for these artifacts are asymptotic. Radii for a space-based centrifuge are dictated by the diameter of the laboratory and are, therefore, in the range of 4 to 10 ft. Conceivably, the steep acceleration gradient and high angular velocity associated with a short-radius centrifuge could produce a force environment unsuitable for refresher or readiness training during prolonged orbital flight. It was the purpose of this study, therefore, to examine the effects of the force environment produced by a short-radius centrifuge on motor skills required during entry.

The experimental plan provided answers to these analogous questions: (1) the effects of practicing entry on a long-radius centrifuge on the ground and, subsequently, testing entry performance on a short-radius centrifuge in space; (2) the effects of practicing entry on a short-radius centrifuge in orbit and, then, performing an actual entry; (3) the differences between dynamic and static simulation of the entry task. The study complements that of Cable (ref. 2), who studied the effects of the force environment produced by a short-radius centrifuge on reaching performance.

METHOD

Force Environment

When using a centrifuge of finite radius as an analog for gravitational fields or accelerations created by unidirectional forces, such as thrust or drag, two inherent artifacts must be recognized. One is acceleration gradient and the other is the Coriolis acceleration.

Acceleration gradient is brought about by the fact that, at constant angular velocity, those parts of a mass on the centrifuge farthest away from the center of rotation are subject to higher centrifugal forces than mass elements nearer the center of rotation. Thus, when a subject riding the centrifuge moves his arm from a 64-in. radius to a 48-in. radius point he experiences a decreasing force field. Fig. 1 is a nomograph for determining acceleration gradient and angular velocity for radii up to 250 in.*

Coriolis acceleration manifests itself only when there is a velocity present with respect to a rotating system. As an example, suppose a man attempts to reach outward from the center of rotation while the centrifuge is spinning. Because tangential velocity is equal to the angular velocity multiplied by the radius, the tangential velocity of his arm must increase as the reach increases. In order to change velocity a force which equals mass times acceleration must be present. This acceleration is called the Coriolis acceleration, which is equal in magnitude to the Coriolis force divided by the mass. The Coriolis acceleration is proportional to the angular velocity of

*A straight line drawn from a point on Scale A to a point on Scale C will intersect Scale B to give rotational speed for a selected acceleration and radius. A straight line drawn from a point on Scale C to a point on Scale D will intersect the diagonal. A different line drawn through this point and Scale E will intersect Scale F and give the acceleration gradient corresponding to points selected on Scales C, D, and E.

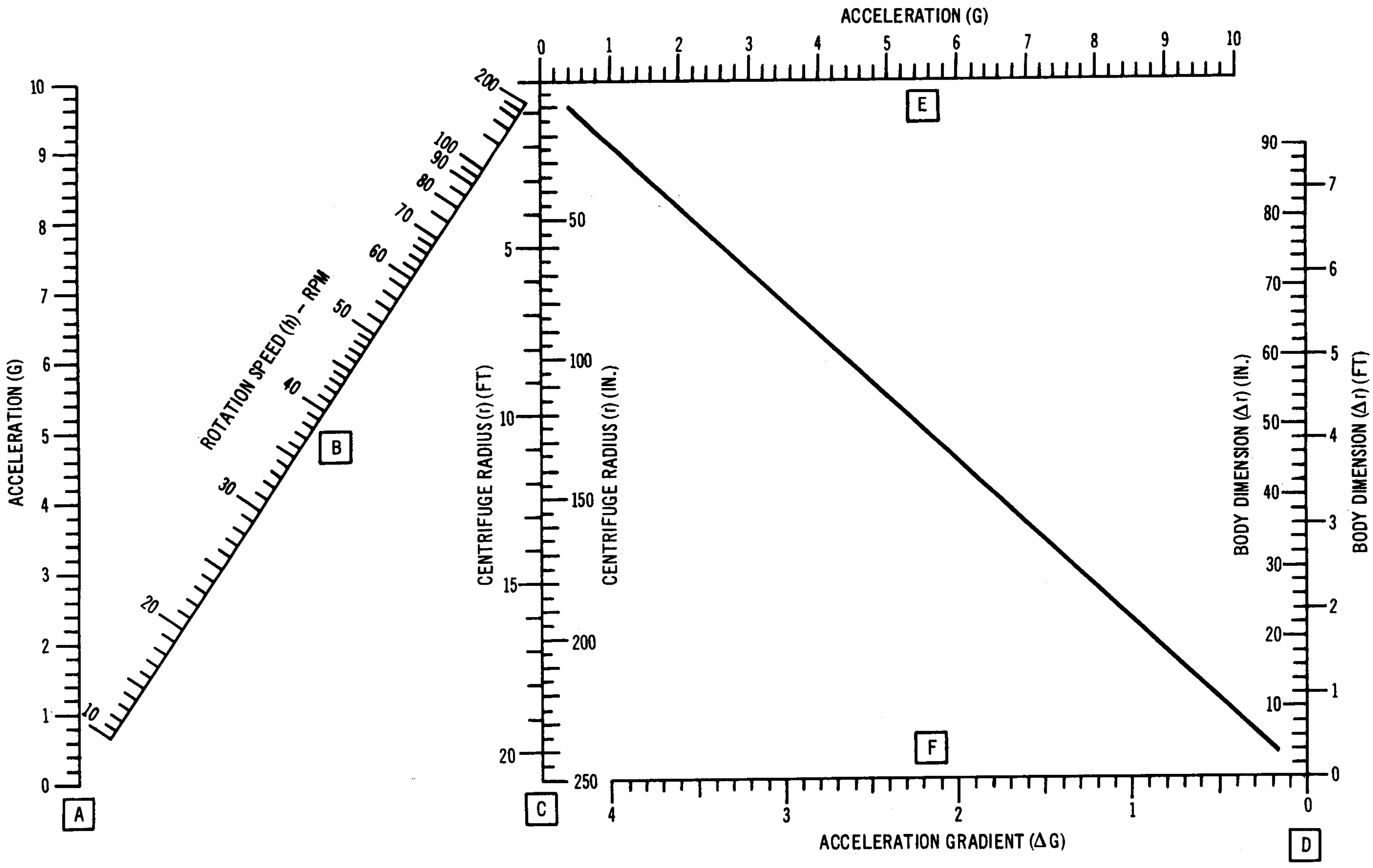

Figure 1. Nomograph for Determining Acceleration Gradient and Angular Velocity

the centrifuge and the velocity along the arm. The Coriolis force acts at an angle of 90° to the path of the arm, tending to deflect the arm. Thus, a man moving his hand along a ray line while riding a spinning centrifuge will have his hand deflected to the side by the Coriolis acceleration.

The entry acceleration environment of this study was produced by the centrifuge shown in fig. 2. Two radii were used. When the chair was in the short-radius position, the distance from the center of rotation to the subject's heart was 64 in.; in the long-radius position, this distance was 178 in. The subject faced toward the center of rotation and was exposed to acceleration in the $+g_x$ direction. All subjects were exposed to the acceleration profile shown in fig. 3. During the first 80 sec of the profile, the subject performed a discrete task which involved a series of response sequences measured in terms of reaction, reach, and adjustment times. During the remaining 120 sec, the subject performed a tracking task which involved minimizing cross-range error and deviation from a nominal entry profile. The control inputs of the subjects did not produce a change in the angular velocity of the centrifuge.

Experimental Plan

The study was divided into 4 experimental periods. The 10 subjects were placed in two groups of 5 each. Both groups made a series of 10 static runs, before and after a series of dynamic runs. The difference between Groups I and II was the order in which they rode each radius. Group I started with the 64-in. radius and finished on the 178-in. radius. Group II made dynamic runs in the reverse order. This plan allowed for a comparison of performance during dynamic and static simulation and of the effects of centrifuge radius on performance. The order in which the groups rode the centrifuge minimized the effects of performance improvement as a result of practice; the static runs at the end of the dynamic testing made possible the quantitative statement about practice effects.

The discrete response and tracking tasks used in the study are representative of the basic motor skills required during entry. The former corresponds to emergency corrective actions which might be required during entry; the

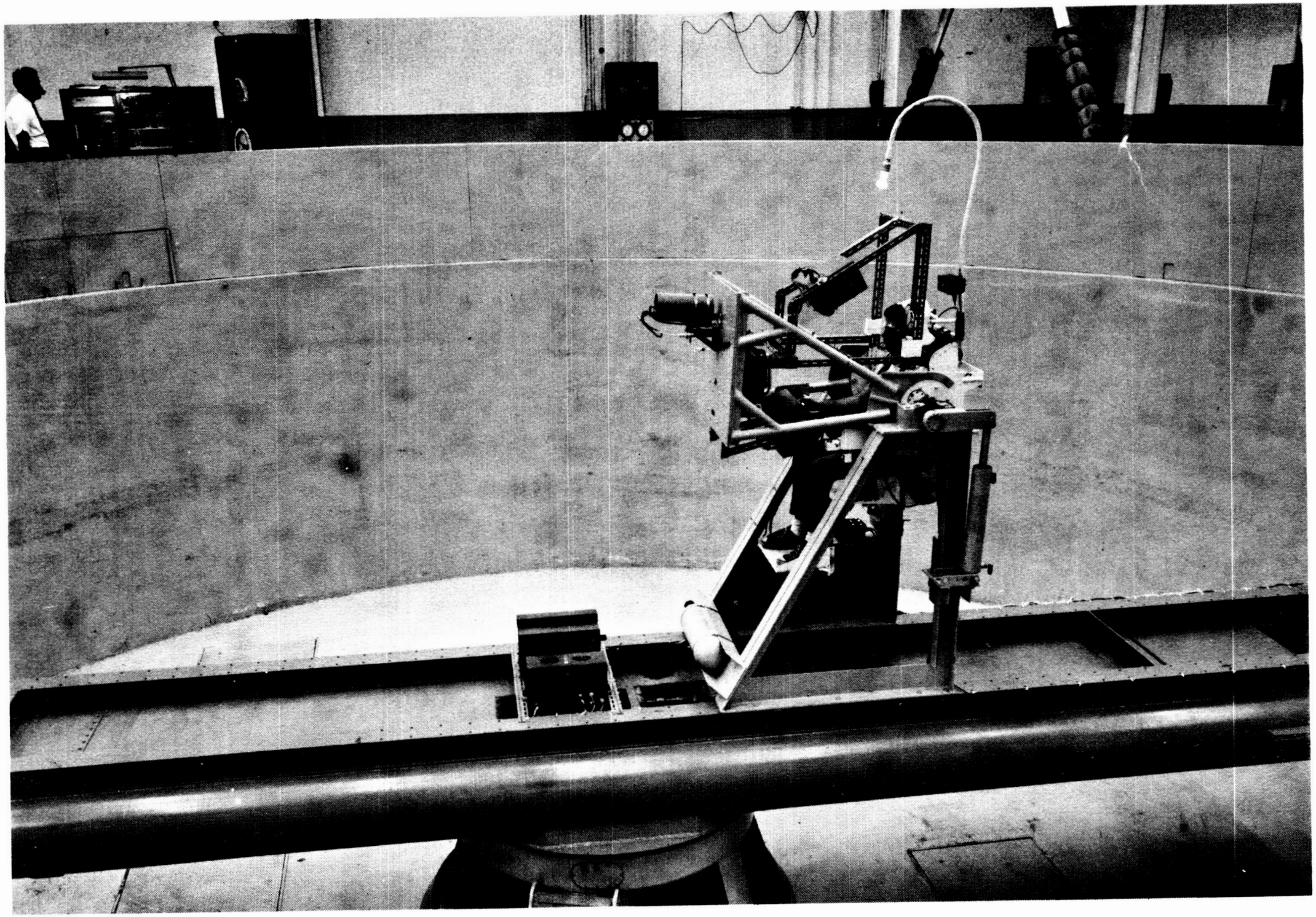

Figure 2. Douglas Centrifuge Configured for an Entry Run at a Radius of 64 in.

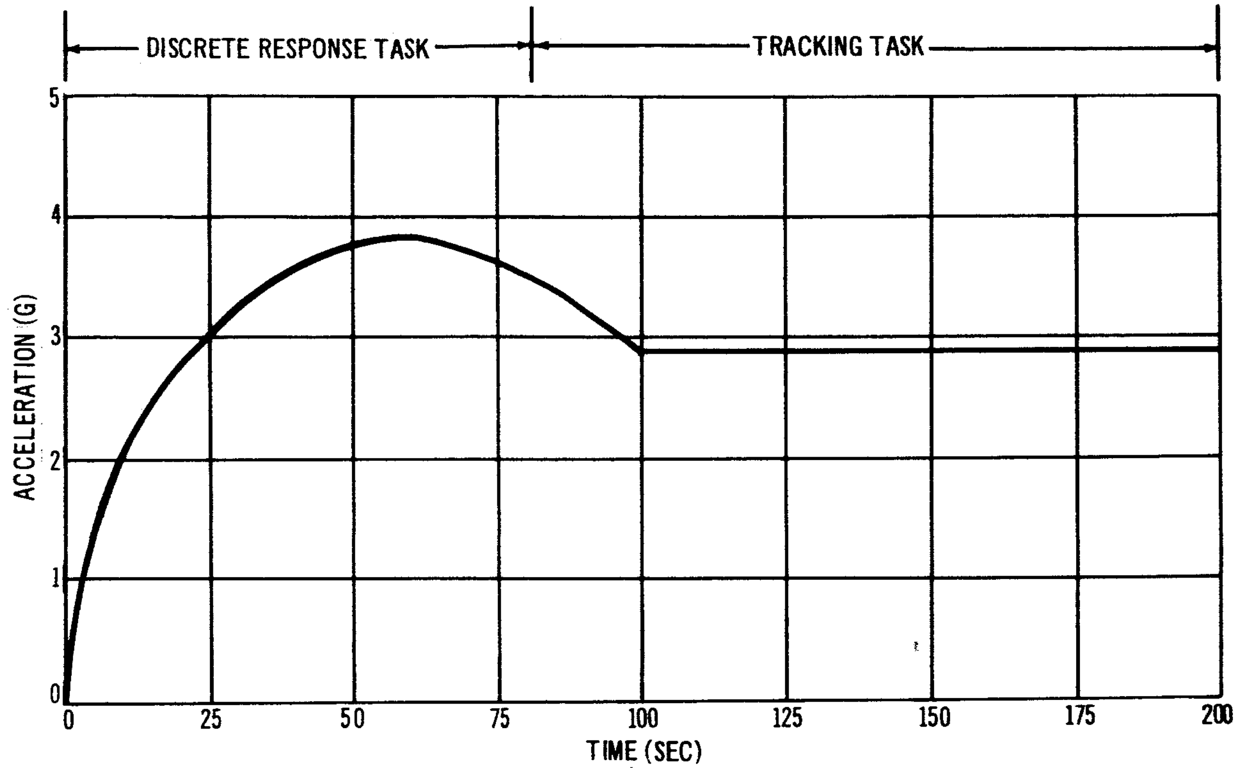

Figure 3. Relation of Performance Tasks to the Acceleration Profile

latter corresponds to the manual-control override which might occur in an Apollo-type vehicle prior to capture of the vehicle by the atmosphere.

The discrete response task was presented to the subject on two identical consoles. Each contained 5 aerospace-type controls: horizontal lever, vertical trim wheel, rotary knob, pushbutton, and a toggle switch. One console was located ahead of the subject, below the entry monitor display, and at arm's length for the subject with the shortest reach (fig. 4). Another console was located above the subject and was inclined 29° from the vertical toward the subject (fig. 2). The left hand traveled approximately 15 in. from the lap switch to the lower console and approximately 30 in. from the lap switch to the upper console.

A lap switch was strapped on the subject's upper left thigh. The subject's left hand rested on the lap switch until a red light appeared adjacent to one of the controls, at which time the subject reached to move the control to extinguish the light. The red light indicated the direction in which the subject should move the control. There were two lights on either side of the horizontal

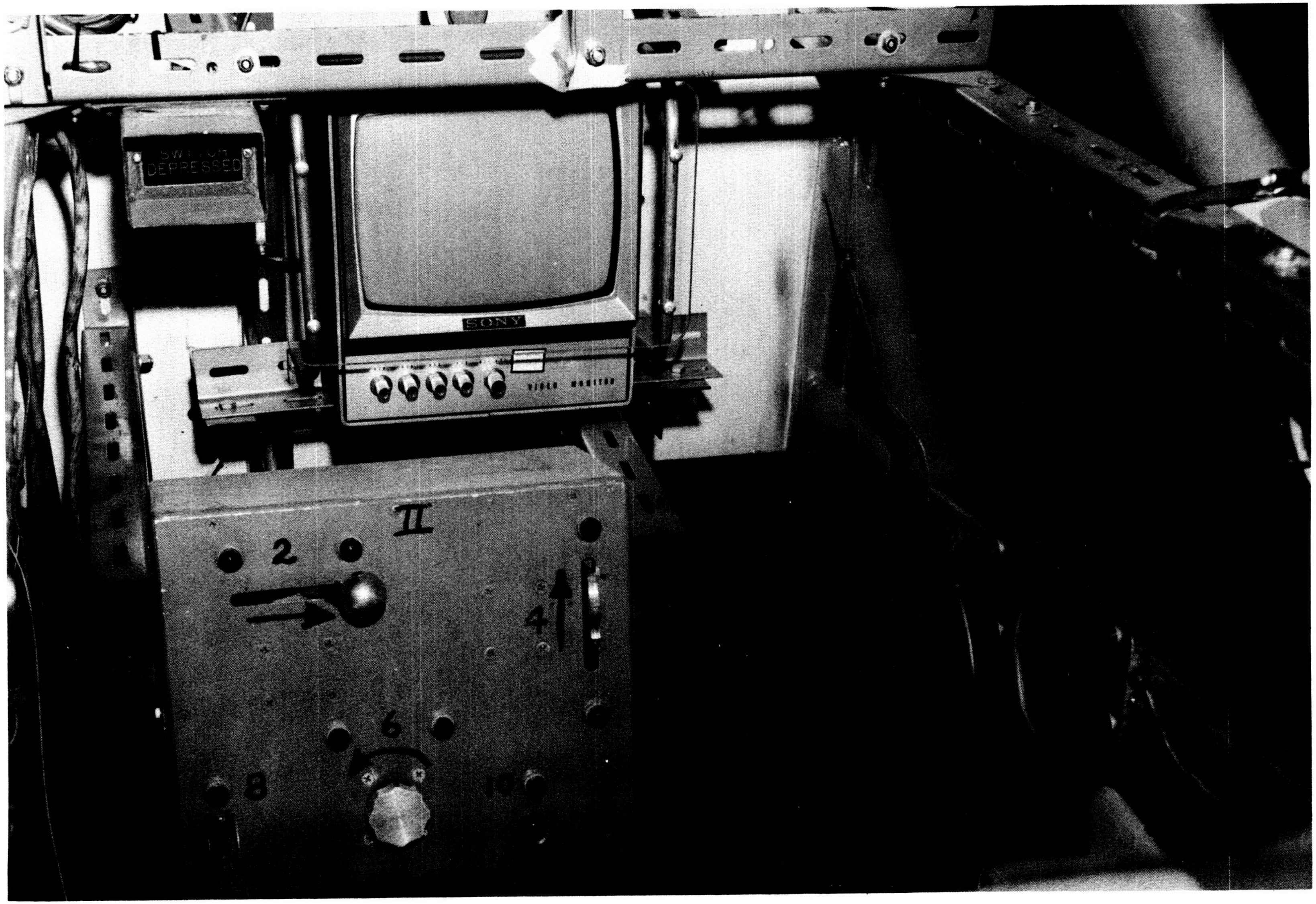

Figure 4. Arrangement of the Control and Tracking Tasks on the Centrifuge

lever, vertical wheel, and rotary knob. If the subject overcontrolled the second light came on, and it became necessary for the subject to adjust the control so that both lights were out. There was only one light for the toggle switch and for the pushbutton. The subject was told when the task should begin. The lights were activated always in the same sequence. The light adjacent to the horizontal lever on the upper-control box came on first and was followed by the light adjacent to the corresponding control in the lower box. The lights continued to alternate between the consoles in this manner throughout the sequence of 10 activations.

The discrete response task was subject-paced. The experimenter pushed a button to activate each signal light immediately after the previous response had been completed. The task commenced with the start of each test run and generally required about 60 sec to complete. During this period, the subject completed 10 control activations (5 on each console); reset the lever, wheel, and rotary controls back to a start position; and completed a second set of 10 control activations. A maximum of 80 sec was allotted for this task.

During the dynamic runs, the subject began the first series of 10 control activations as the centrifugal acceleration increased from zero. At the end of this series, the acceleration was slightly under +3 g_x and was slightly over this value as the subject started the second series of 10 control activations. At the end of this series, the centrifugal acceleration was approximately +3.8 g_x, the maximum attained. Thus, there was a continual change in the magnitude of centrifugal acceleration and Coriolis force during performance of the discrete response task.

Performance on the discrete response task was measured in terms of the following:

(1) Reaction time--Elapsed time between appearance of a red light and the removal of the subject's hand from the lap switch.

(2) Reach time--Elapsed time between removal of the subject's hand from the lap switch until he touched the appropriate control.

(3) Adjustment time--Elapsed time between first touch of the designated control and the final proper positioning of the control. This time was not measured when operating the toggle switch or the pushbutton, as neither was adjustable.

The tracking task was presented to the subject on a closed-circuit television monitor located directly ahead and slightly below his eye level. The picture on the monitor included roll and cross-range error meters and an Apollo*-type-entry monitor display (fig. 5). Manual inputs were made with a roll controller located near the subject's right hand. Maximum deflection of the controller produced a roll rate of 15°/sec. Maximum lift was indicated on the roll meter when the pointer was at 0°; maximum drag was indicated at 180°; and at 90° on either side of 0°, the lift-to-drag ratio equaled unity. Maximum lift or drag produced a rate of change of acceleration at 0.24 g/sec. At intermediate ratios the cross-range error was continuously integrated and displayed on a meter. One of the subject's tasks was to minimize this error and, therefore, the lateral displacement of a nominal point of touchdown. The diagram appearing on the entry monitor indicated excessive acceleration and skipout conditions as they appeared on the Apollo display. The pen moving across this display indicated the acceleration profile. The pen moved at a constant rate along the X-axis; its movement along the Y-axis was determined by the subject's control inputs. The task of the subject was to minimize deviations from a nominal entry profile. The forcing function used during static and dynamic runs approximated a sine wave of 0.02 cps. It caused the acceleration to change at a maximum rate of 0.18 g/sec.

At the beginning of the tracking task, the subject was required to move the roll control to reduce lift and then to maintain a constant acceleration while keeping cross-range error to a minimum. Vehicle trajectory was determined by algebraic addition of the forcing function and the lift or drag resulting from the vehicle roll angle. The purpose of the forcing function was to simulate variations in atmospheric density and, thereby, make the subject's task more difficult. The subject compensated for the forcing function by rolling the vehicle to achieve the required amount of lift or drag.

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*A prototype of the Apollo entry monitor display was provided by North American Aviation, Autonetics Division, for a preliminary study of this part of the tracking task.

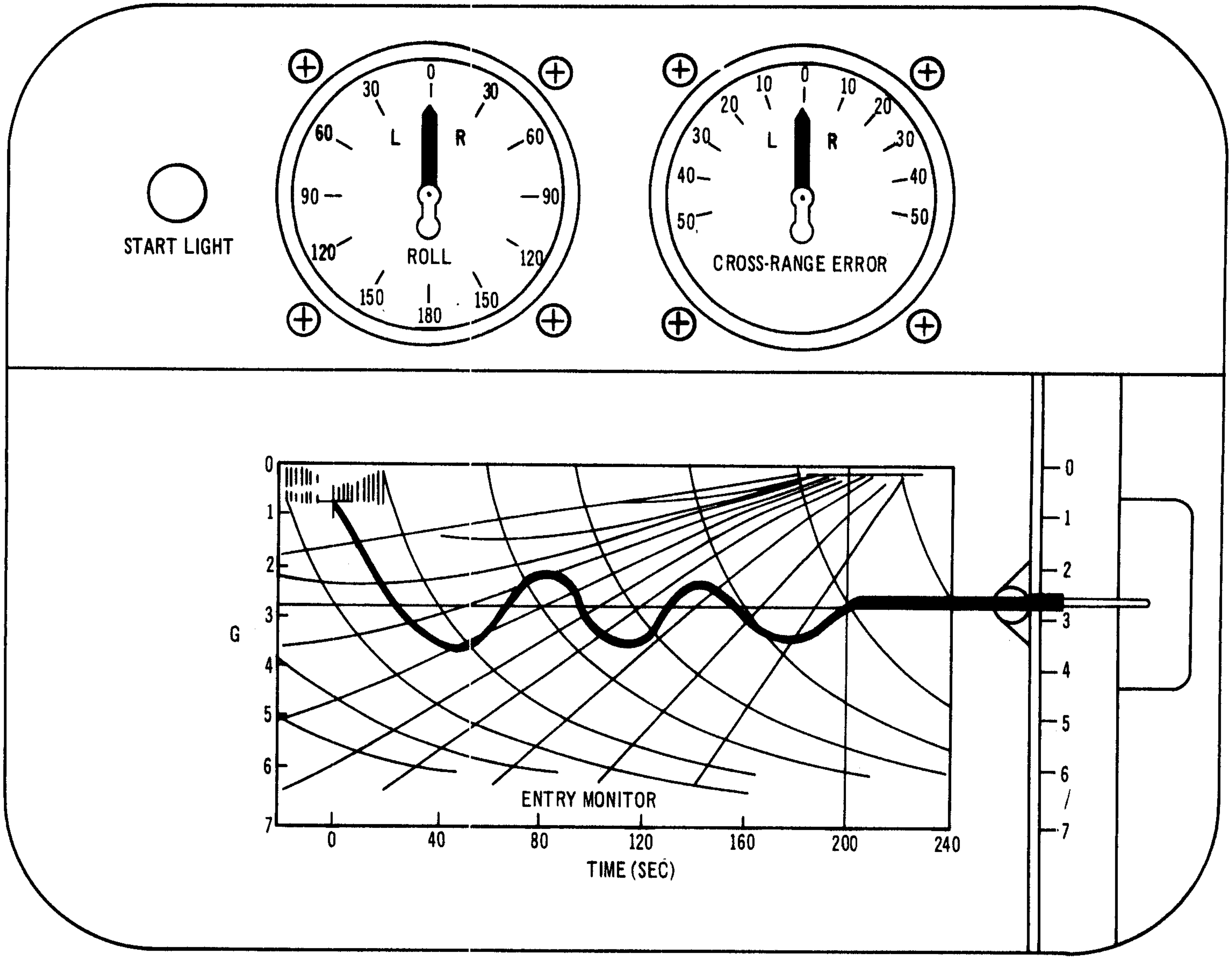

Figure 5. Tracking Task Display-Elements: Start Light, Roll and Cross-Range Meters, and Entry-Monitor Display

Tracking performance was recorded during the last 120 sec of the run. During the dynamic runs, the subject began tracking while the acceleration was +3.6 g_x and decaying. The acceleration leveled off at +2.8 g_x, where it remained constant until the end of the tracking task. Entry-monitor performance was evaluated in terms of the average absolute deviation of the vehicle acceleration from the nominal entry, and cross-range performance was measured in terms of the average absolute deviation of the cross-range error pointer from zero. Performance scores are based on that portion of the run at which a steady-state acceleration existed.

Subjects

The 10 subjects were studied during 4 days of training and 16 days of testing. Before training the subjects received one hour of orientation including rides on the centrifuge. Training consisted of two 1-hour periods of practice on the discrete-response and tracking tasks. At the completion of training, the subjects were ranked in terms of their performance on the control-box task, and on the entry-monitor task. The two performance ranks for each subject were added, and the subjects were ranked accordingly. From this combined ranking, the subjects were placed in two groups in such a manner that the mean and variance of the ranks for each group were as nearly equal as possible. The mean ranks of Groups I and II were 5.4 and 5.6, respectively, with a rank of 1 indicating best performance on the combination of the two tasks. The schedule was as follows:

Group I	Group II	Sessions
Orientation	Orientation	1
Training	Training	2
Static centrifuge	Static centrifuge	2
Dynamic centrifuge	Dynamic centrifuge	
64-in. radius	178-in. radius	2
178-in. radius	64-in. radius	2
Static centrifuge	Static centrifuge	2

A training session consisted of 10 runs for each subject per session; a test session consisted of 5 runs for each subject per session.

Medical history, physical examination, Master's ECG, urinalysis, and blood analysis of each subject were normal. All subjects were paid volunteers and were free to withdraw from the experiment at any time. Prior to the study, the subjects were briefed on the nature of the experiment, probable risks, and steps taken to insure their health and welfare. The ages of the subjects ranged from 21 to 26 years. ECG's were taken continuously during centrifugation. Except for changes commonly seen with increased heart rate, all were within normal limits. Reports by the subjects and observations by the experimenters indicated that the experimental conditions did not preclude movement of the head, arms, and legs; however, no motion sickness occurred during the experiments. The subjects were in voice contact with the experimenters at all times.

RESULTS

Discrete Response Task

Results of the discrete response task are summarized in Table I in terms of the mean and standard deviation of the response time for each group, experimental condition, and response phase. The average response time was 1.4 sec; the greatest difference was 0.36 sec. Various comparisons are possible, and statistical inferences were made by use of nonparametric techniques.

The mean reaction time for Group II (0.45 sec) was significantly higher ($P^{*} < 0.01$) than that for Group I (0.38 sec). Reaction time on the moving centrifuge (0.44 sec) was significantly higher ($P < 0.01$) than reaction time on the static centrifuge (0.38 sec), and reaction time on the moving centrifuge was significantly higher ($P < 0.01$) with a long radius (0.48 sec) than with a short radius (0.40 sec). Reaction time to the upper-control console (0.41 sec) was the same as to the lower-control console (0.41 sec).

When similar conditions are compared, only 2 comparisons are significant ($P < 0.05$)--(Group II upper and lower consoles at the long radius). Comparison of reaction times on the 1st and 8th days of the study showed a 4% improvement.

Mean reach time for Group I (0.44 sec) was not significantly different from that for Group II (0.46 sec). Mean reach time was significantly longer ($P < 0.01$ sec) when the centrifuge was turning (0.49 sec) than when it was stationary (0.40 sec); it was significantly longer ($P < 0.01$) on the long radius (0.55 sec) than on the short radius (0.45 sec). Mean reach time to the upper console (0.50 sec) was significantly longer ($P < 0.01$) than to the lower console (0.39 sec). This latter result would be predicted because the hand traveled 30 in. to the upper console and 15 in. to the lower.

When similar conditions are compared only 4 comparisons are significant ($P < 0.02$)--(Group I lower console, short radius, Group II upper console static, and both consoles at the long radius). Comparison of reach

*P refers to the probability of a difference this large occurring by chance.

TABLE I

DISCRETE RESPONSE TASK--SUMMARY

Group	Condition	Reaction Time				Reach Time				Adjustment Time			
		Upper Console		Lower Console		Upper Console		Lower Console		Upper Console		Lower Console	
		Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
I	Static-1	0.33	0.017	0.32	0.018	0.51	0.015	0.42	0.016	0.47	0.038	0.58	0.028
	Static-2	0.32	0.015	0.32	0.022	0.48	0.019	0.39	0.022	0.45	0.064	0.56	0.042
	Short Radius-1	0.37	0.036	0.36	0.030	0.62	0.031	0.53	0.039	0.61	0.092	0.66	0.091
	Short Radius-2	0.38	0.015	0.38	0.021	0.55	0.011	0.42	0.017	0.44	0.027	0.57	0.014
	Long Radius-1	0.44	0.023	0.47	0.032	0.49	0.014	0.35	0.014	0.47	0.046	0.57	0.033
	Long Radius-2	0.44	0.015	0.45	0.011	0.50	0.023	0.35	0.011	0.47	0.028	0.56	0.033
	Static-3	0.38	0.024	0.36	0.015	0.41	0.017	0.32	0.026	0.39	0.034	0.47	0.041
	Static-4	0.36	0.019	0.37	0.022	0.40	0.022	0.30	0.012	0.35	0.024	0.43	0.037
II	Static-1	0.46	0.020	0.47	0.024	0.48	0.018	0.38	0.015	0.48	0.027	0.59	0.032
	Static-2	0.45	0.017	0.46	0.010	0.42	0.021	0.33	0.021	0.53	0.041	0.60	0.019
	Long Radius-1	0.46	0.026	0.49	0.033	0.55	0.021	0.45	0.025	0.64	0.053	0.74	0.055
	Long Radius-2	0.52	0.028	0.53	0.029	0.49	0.038	0.40	0.027	0.59	0.055	0.69	0.069
	Short Radius-1	0.45	0.020	0.44	0.014	0.60	0.031	0.49	0.028	0.58	0.038	0.67	0.030
	Short Radius-2	0.43	0.021	0.43	0.010	0.60	0.029	0.48	0.013	0.50	0.054	0.64	0.041
	Static-3	0.38	0.019	0.40	0.008	0.48	0.013	0.37	0.012	0.54	0.029	0.59	0.058
	Static-4	0.39	0.007	0.39	0.007	0.45	0.012	0.34	0.021	0.54	0.045	0.53	0.039

Note: Entries are in seconds for mean and standard deviation (S.D.)

times on the 1st and 8th days of the study showed that reach time to the upper console was 14% less on the 8th day, and the time to the lower console was 20% less.

The mean adjustment time for Group II (0.59 sec) was significantly higher (<0.01 sec) than for Group I (0.50 sec). It was significantly higher ($P<0.01$ sec) when the centrifuge was moving (0.59 sec) than when it was stationary (0.51 sec). However, there was no significant difference between the short radius (0.58 sec) and the long radius (0.59 sec). The mean adjustment time for the lower console (0.59 sec) was significantly greater ($P<0.01$) than for the upper console (0.50 sec).

When similar conditions are compared only 3 comparisons are significant ($P<0.01$)--(Group I upper and lower console, short radius and Group II lower console, long radius). Comparison of adjustment time for the 1st and 8th day of the study showed that it decreased by 12%.

Tracking Task

Results of the tracking task are summarized in Table II for each group, experimental condition, and performance measure. The cross-range error is presented in terms of mean deviation from an assigned value of zero. Entry-monitor error is presented in terms of deviations in units of acceleration from an assigned value of $+2.8\ g_x$.

Entry-monitor error on the moving centrifuge (0.27 g) was significantly higher ($P<0.01$) than on the static centrifuge (0.26 g), and it was significantly higher ($P<0.01$) on the short-radius centrifuge (0.29 g) than it was on the long-radius centrifuge (0.26 g). The performance of Group I (0.26 g) was not significantly different from that of Group II (0.27 g). Neither was there a significant difference between the groups in cross-range error. There was a significant difference between the errors from the static runs (8.72) compared with the dynamic runs (9.11) and from the runs on the long-radius centrifuge (8.54) compared with the short-radius centrifuge (9.69). Entry-monitor and cross-range error performance improved approximately 9% between the 1st and 8th day of the study.

TABLE II

TRACKING TASK--SUMMARY

Group	Condition	Entry-Monitor Error		Cross-Range Error	
		Mean	S. D.	Mean	S. D.
I	Static-1	0.29	0.028	9.58*	0.49
	Static-2	0.25	0.017	9.12	0.85
	Short Radius-1	0.31	0.013	9.90	0.38
	Short Radius-2	0.27	0.020	9.69	0.69
	Long Radius-1	0.26	0.010	8.13	0.29
	Long Radius-2	0.21	0.014	8.23	0.30
	Static-3	0.22	0.019	7.60	0.44
	Static-4	0.23	0.023	7.86	0.38
II	Static-1	0.26	0.026	9.04	0.30
	Static-2	0.25	0.023	8.03	0.22
	Long Radius-1	0.27	0.036	8.98	0.31
	Long Radius-2	0.28	0.013	8.80	0.41
	Short Radius-1	0.28	0.006	9.62	0.61
	Short Radius-2	0.30	0.015	9.54	0.56
	Static-3	0.28	0.017	9.32	0.29
	Static-4	0.26	0.014	9.19	0.25

Notes: (1) Entries are in g units for entry monitor and in arbitrary units for cross-range.

(2)* Corresponds to a lateral displacement of approximately 4.5 mi from the nominal point of touchdown.

Transfer of Training Effects

The effect of performance on the short-radius centrifuge upon subsequent performance on the long-radius centrifuge was evaluated by examining the difference between mean performance for the 2nd baseline day and the 1st day at the long radius, both with and without the interposition of performance on the short radius. This method of examination minimizes the effect of differences between the two groups because each subject's baseline score, representing his level of ability on the task, was subtracted from his score at the long radius. The resulting difference in performance between the 2 groups at the long radius should result primarily from the fact that Group I had performed for 2 days on the short radius, whereas Group II had not. Evaluation of transfer effects was performed with the measures for reach time and entry-monitor error.

When the subjects went directly from the 2nd baseline session to the long radius, their reach time to the upper console increased by 0.13 sec, reach time to the lower console increased by 0.12 sec, and the entry-monitor tracking error increased by 0.02 g. When the subjects went to the long radius after having performed for 2 days on the short radius, their reach time to the upper console increased 0.01 sec over the baseline measure, reach time to the lower console decreased by 0.04 sec, and the entry-monitor error increased by 0.01 g. Examination of these results shows that positive transfer did result from the experience on the short-radius centrifuge, in that net performance at the long radius improved for all three measures.

When the subjects went directly from the 2nd baseline session to the short radius, their reach time to the upper console increased by 0.14 sec, reach time to the lower console increased by 0.14 sec, and the entry-monitor tracking error increased by 0.06 g. When the subjects went to the short radius after having performed for two days at the long radius, reach time to the upper console increased by 0.18 sec over the baseline measure, reach time to the lower console increased by 0.16 sec, and the entry-monitor error increased by 0.03 g. The data showed that negative transfer resulted from the long-radius experience, in that net performance decreased for all 3 measures.

DISCUSSION

The reaching movements, included in the discrete response tank, represented those control responses required during manual or semimanual entry, which should be affected most by changes in the force environment. In addition, the movements were made during the phase of entry when the force field would be changing most rapidly. During this period, the force against which a subject had to work in reaching toward the center of rotation for a control on the lower console varied from 10 lb, the assumed weight of his arm at 1 g, to 40 lb at the peak of approximately +4 g_x. At the same time, the Coriolis force, tending to move his arm to the right, varied from 0 to approximately 6 lb when the centrifuge radius was 178 in. and from 0 to approximately 10 lb when the centrifuge radius was 64 in.

In spite of the large variation in the force environment, mean reach time to the control consoles increased by only 0.09 sec when the centrifuge was moving compared to the static test conditions, and mean reach time at the short radius was only 0.1 sec longer than it was at the long radius. In each case, the increase is approximately 22%. This is somewhat more than the 15% increase in reaching time obtained by Cable (ref. 2) after the Coriolis force and force gradient were increased by a factor of 2.5 to 1. In that study, the acceleration was constant at +2.5 g_x during the reaching task; in this study, it varied from 0 to +3.8 g_x. The range of variation in reaching time, obtained in each of these two studies, resulting from changes in the force environment, was well within the range of times obtained by Green and Muckler (ref. 3) for reaching to critical control areas in a fighter-type cockpit. These authors found that mean speed of reaching changed as much as 37% between the different control areas and that it changed 13% when the control areas were adjacent.

The change in centrifuge radius should have had more effect on reach time to the lower console than to the upper console, because reaching movements to the lower console are more affected by the concomitant change in Coriolis force. This was found to be the case in that mean reach time to the lower console was 23% longer at the short radius than at the long radius, while mean reach time to the upper console was 16% longer at the short radius than at the long radius.

Both reaction time and adjustment time were longer on the moving centrifuge than on the static centrifuge. This is reasonable, because all movements are more difficult when the centrifuge is moving. However, it is difficult to explain why reaction time was consistently longer on the long radius than on the short radius. Table I shows that this is true for Group-I and Group-II responses to the upper and lower consoles. One possible explanation is that the shorter reaction time on the short radius may have resulted from compensation by the subjects. If the subjects were trying harder on the short radius to compensate for the less favorable force environment, their efforts would have more effect in improving performance on a task, such as reaction time, which should not be appreciably affected by less favorable conditions.

Predictably, the continuous tracking measures were less affected by changes in the force environment than the reaching movements. The entry monitor and cross-range tracking errors were 4 to 6% larger when the centrifuge was moving than when it was static, and they were approximately 12% larger on the short-radius than on the long-radius centrifuge. Although several of the variations in tracking proficiency were statistically significant, they were not large compared with normal variations in performance.

The finding of positive transfer of training in going from a short radius to a long radius would appear to provide support for the application of an onboard centrifuge for entry training. The change in both the Coriolis force and the force gradient, brought about by the change in radius from 64 to 178 in., amounted to approximately 40% of the change in those forces that would be encountered by an astronaut in going from an onboard centrifuge with a radius of 64 in. to actual entry. Thus, even though the change in radius was small, it resulted in a proportionately large change in the force environment. However, in considering the application of these results to space problems, it is necessary to reconcile the positive transfer, obtained in going from the short to the long radius, with the negative transfer, obtained in going from the long to the short radius. The reason for this difference in transfer is not immediately apparent. It does not appear to have resulted from an experimental artifact because it occurred to an appreciable degree with all three of the performance measures considered. Additional research to isolate the factors responsible for the difference in transfer may be required.

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