

**THE EFFECT OF CORIOLIS FORCES ON PERFORMANCE OF
TWO-HANDED TASKS**

by
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The Effect Of Coriolis Forces On Performance Of Two-Handed Tasks

by

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Submitted to the Department of Aeronautics and Astronautics on December 20, 1996 in Partial Fulfillment of the Requirement for the Degree of Master of Science in Aeronautics and Astronautics

ABSTRACT

Artificial gravity is one of the proposed measures for preventing physiological deconditioning during long term space missions. However, the Coriolis forces created within a rotating environment cause problems when motions are attempted. Previous research has shown that subjects can adapt to these forces while performing simple tasks. The purpose of this study was to determine if the performance of two-handed tasks was affected by Coriolis forces. In addition, it was questioned whether any decrease in performance did occur, and whether performance could be improved through practice and adaptation to the rotating environment. Finally, performances were compared on two other testing days which were spaced three and five days apart, respectively, to determine if any learned process carried over to subsequent days.

Experiments were conducted with six males and six females on the MIT-Artificial Gravity Simulator (MIT-AGS), a 2 m radius centrifuge. Subjects were rotated clockwise at 20 rpm about an axis perpendicular to their z-body axis. While rotating, subjects performed a modified Stromberg Dexterity Test where they simultaneously exchanged the position of two wooden cylindrical blocks at a time, using both hands. Prerotations and postrotations sessions were conducted on each test day, in addition to a practice session. Two sequences of block exchanges were used, a simple one and a more complex one. The simpler task involved performing exchanges using arm motions which were perpendicular to those used in the more complex sequence.

Data was analyzed through repeated measures analysis of variance. It was found that although there was no significant difference in performance between the prerotation, perrotation, and postrotation conditions as a whole, there was a significant decrease in performance during the first trials of each perrotation and postrotation session ($p < 0.05$). An increase in performance occurred in the remaining two trials of each experimental condition. A learning curve was present in the performance of both test sequences. However, the learning curve for the more complex sequence was more pronounced. It was concluded that Coriolis forces do affect the performance of two-handed tasks. However, subjects adapted to the rotating and nonrotating environments quickly so as to not affect the overall performance of their test sessions.

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1.0 Introduction

One of the proposed means of preventing physiological deconditioning during long-term space missions, such as a trip to Mars, is to create artificial gravity by rotating the spacecraft. However, while artificial gravity may help prevent the physiological problems induced by microgravity, the resulting gravity gradients and Coriolis forces may cause problems when attempting normal motions (Loret, 1963; Stone, 1970; Ramsey, 1971; Lackner, 1993). Since artificial gravity is the centrifugal force created by rotation, $a_{\text{cent}} = r\omega^2$, a trade-off exists between rotation rate (ω) and vehicle radius (r). A 1 G centripetal force may be created by a rotation rate of approximately 1 rpm with a 900 m radius or with a rotation rate of approximately 10 rpm and only 9m radius. The relationship between rotation rate and vehicle radius is shown in Figure 1-1.

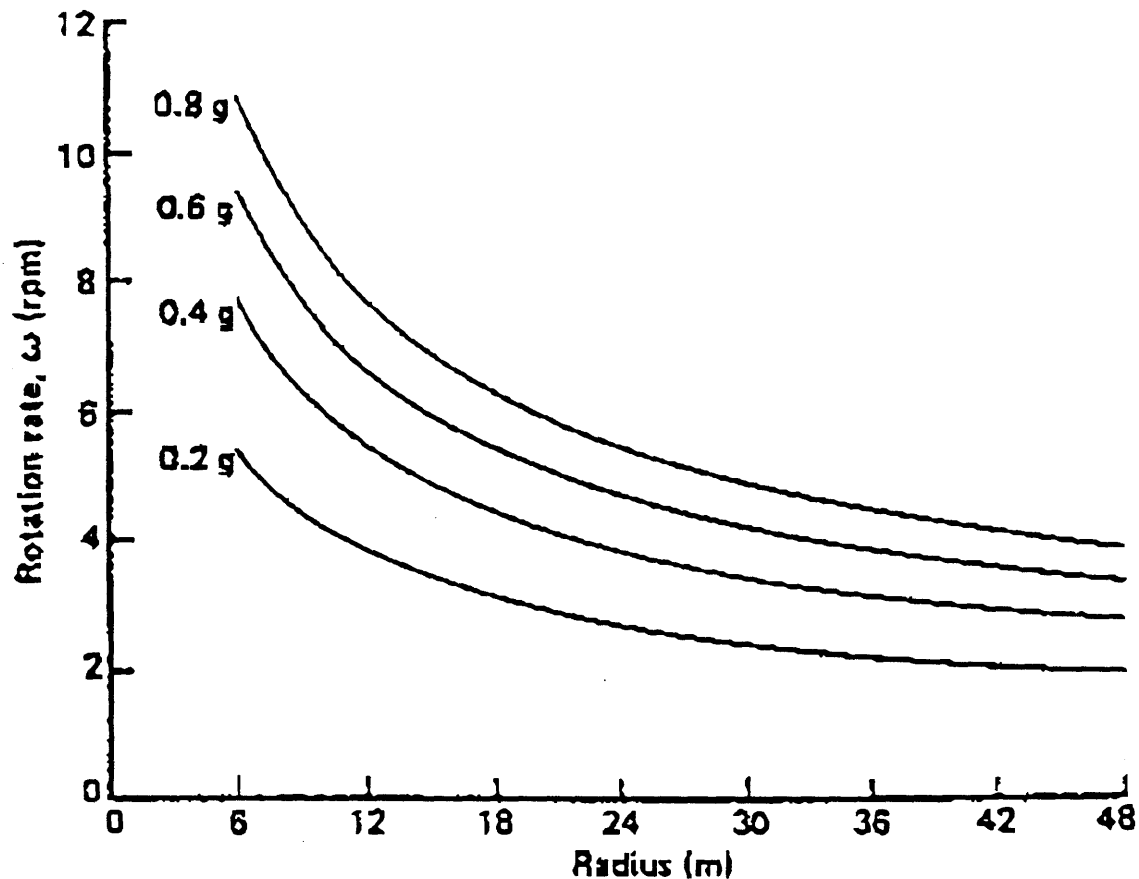


Figure 1-1 Rotation Rate Versus Radius (Stone, 1970)

Ever since the idea of rotating space vehicles evolved, research has been conducted on the effects of rotational forces on human performance. The studies conducted at the Pensacola Slow Rotation Room (SRR) consisted of various tests to assess human performance while in a rotating environment. However, the researchers were primarily concerned with the effects on the vestibular system and the brain-stem activating system (Graybiel, Clark, and Zarriello, 1960; Clark and Graybiel, 1961; Kennedy and Graybiel, 1962; Graybiel et al., 1965; Guedry, 1962). In addition, the subjects in the SRR were not oriented as they would be in an artificial gravity environment. In a rotating space environment, astronauts will stand perpendicular to the axis of rotation, with their feet on the “walls”, whereas in the SRR they stand on the “floor”. Studies conducted by the North American Rockwell Corporation and Langley Research Center were in the correct orientation. However, experiments involving complex two-handed tasks were not conducted (Piland et al., 1970; Green and Peacock 1972; Stone and Letko, 1962a, 1962b, 1964).

The object of the current study was to investigate how the Coriolis forces created by rotation affect the central nervous system’s ability to perform gross motor tasks requiring two-handed hand-eye coordination. The study was motivated by the fact that astronauts must be able to complete their required tasks efficiently while experiencing artificial gravity. According to previous studies, both sense of limb position and execution of motions are influenced by force environment (Lackner, 1993). A model of how arm movement could be monitored was proposed by Lackner and can be seen in Figure 1-2. This model showed how deviations from expected trajectories could be modified and used to adapt to contact and noncontact forces (such as Coriolis forces).

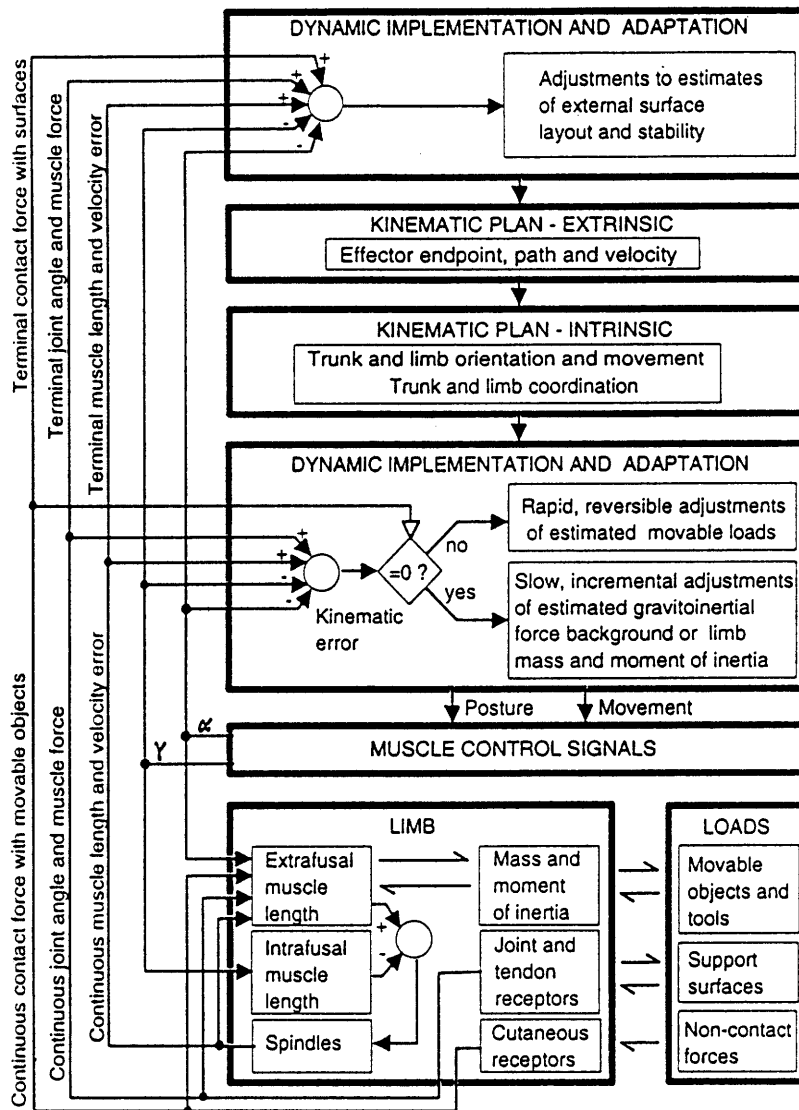


Figure 1-2 Model of Movement Control and Adaptation to Contact and Noncontact Forces (Lackner and DiZio, 1994)

The model incorporated proprioceptive, tactile, and motor signals into the adaptation process. For hand-eye coordination tasks, such as those studied in this project, subjects also received closed-loop visual feedback about accuracy of movements. However, arm movements made in different directions while in a rotating environment, such as those necessary in certain two-handed tasks, experience Coriolis forces in opposing directions. For example, in Sequence A performed by subjects in this study, a subject's arms moved in opposing directions while bringing his arms together and then apart. In this case, according to the relation $F_{\text{cor}} = -2m(\omega \times \underline{v})$, where m is the mass of the subject's arm, ω is

the angular acceleration of the MIT-AGS, and v is the velocity of arm motion, the resulting Coriolis forces were in opposite directions for each arm, as shown in Figure 1-3.

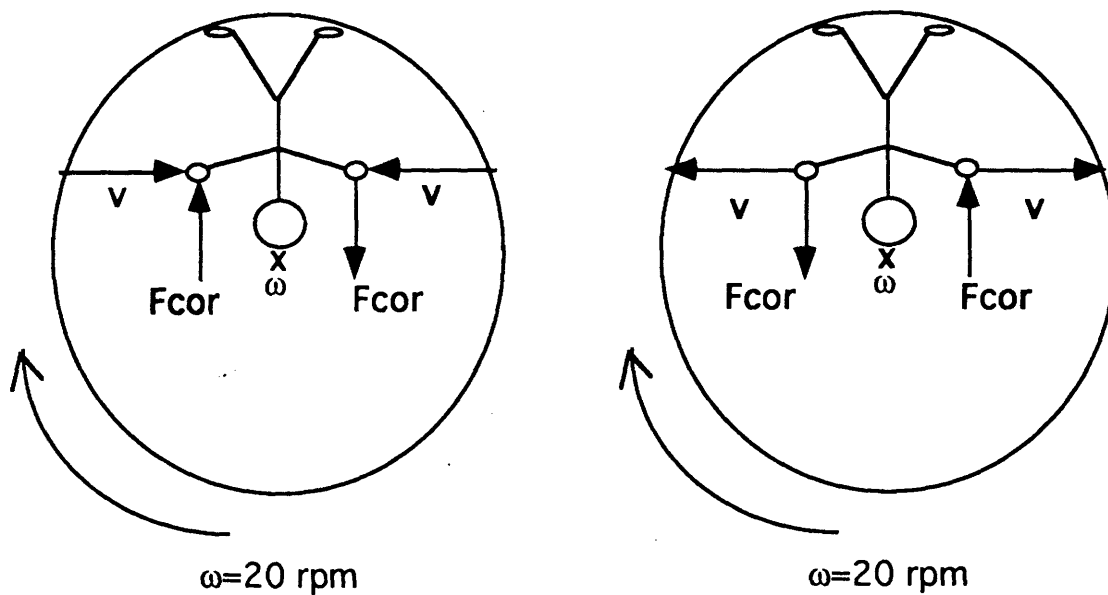


Figure 1-3 Sequence A Arm Movements and Resulting Coriolis Forces

During Sequence B, the Coriolis forces resulting from arm movements were also in different directions for each arm. However, arm movements and the resulting Coriolis forces were perpendicular to those undergone in Sequence A, as shown in Figure 1-4.

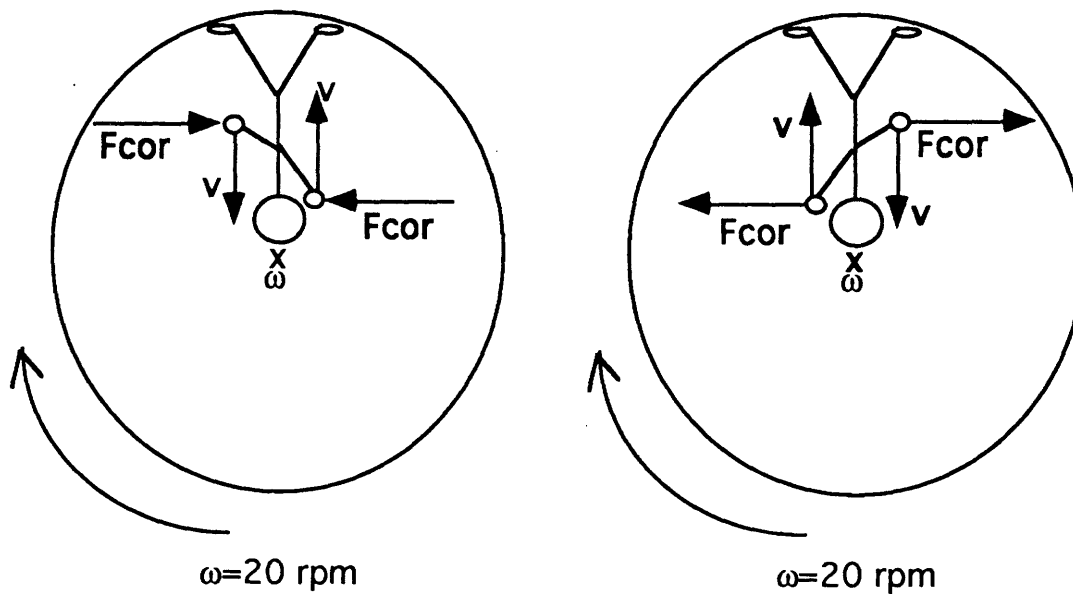


Figure 1-4 Sequence B Arm Movements and Resulting Coriolis Forces

Stone and Letko looked at how Coriolis forces affect the performance of simple perceptual motor skills, as did Lackner and DiZio (1994) with their experiments on the ability of subjects to point at targets while rotating. However, neither used complex two-handed tasks, and Lackner and DiZio performed their experiments with subjects in a different orientation to that of an artificial gravity environment. The point of interest for the current study was to determine if the performance of two-handed tasks was affected while in rotating environment. If so, another interest was to determine if performance improved over time, and to see if improvement in performance was carried over to subsequent days of testing.

2.0 Review of Artificial Gravity Performance Studies

Pensacola Slow Rotation Room

Experiments conducted in the Pensacola Slow Rotation Room (SRR) were designed to observe the effects of living in a rotating environment for a prolonged period. The SRR was a 15 feet diameter, 7 feet high, nearly circular, windowless room which was constructed around the center post of the Pensacola human centrifuge (Graybiel et al., 1960). Studies were conducted with two-day, twelve-day, and fourteen-day periods of rotation.

The initial two-day studies were intended to investigate the effects of prolonged stressful stimulation and to study the adaptation, after-effects, and habituation to the stimulation. Subjects underwent rotation rates ranging from 1.7 rpm to 10 rpm (Graybiel et al., 1960; Clark and Graybiel, 1961). Various tests were performed to stress the subjects by requiring them to move their heads, thus stimulating their semicircular canals. Several tests required minimal head movements, thereby producing low levels of stress, while others required body and/or head movements to serve as severe stressors. The tests and

measurements included electrocardiography, card sorting, determination of blood pressure, hand steadiness, strength of grip, an arithmetic test, body sway, walking, ball throwing, dart throwing, opening locks, and a dial test. Subjects experienced a variety of side-effects which included anxiety, drowsiness, malaise, apathy, visual illusions, nausea, difficulty in walking heel-to-toe, oliguria (having fat in the urine), and shock. One subject who had lost function of his semicircular canals did not experience any unpleasant symptoms, but did experience difficulty in walking before adapting to the centrifugal forces. Subjects adapted easily to rotation rates of 1.7 rpm and 2.22 rpm, but experienced serious side-effects during higher velocities. In some cases, the side-effects were even incapacitating. In addition, after rotation ceased, subjects experienced reoccurrences of the symptoms suffered during rotation, although they were usually not as intense. These research results were used to learn more about psychophysiological mechanisms.

Since visual illusions and mild canal sickness were experienced even at the 1.7 rpm rotation rate, a subsequent two-day study was conducted at 1 rpm to more exactly define what angular velocity would not cause disturbing symptoms (Kennedy and Graybiel, 1962). Similar tests and performance measures were utilized, which included oculogyral illusions, a modified Romberg test, walking, setting five dials arranged around the subject (dial test), a mathematics test, and dart throwing. Subjects with various susceptibilities to motion sickness participated in the study. The increasing levels of susceptibility were defined as normal, very susceptible (above normal), and extremely susceptible. Those subjects within the normal range of susceptibility to motion sickness did not experience any symptoms except slight difficulty walking heel-to-toe with their eyes closed. Subjects with above normal susceptibility to motion sickness experienced no symptoms except apathy after the initial dial test involving 100 head movements. Those with extreme susceptibility to motion sickness experienced mild symptoms, which dissipated after a few hours. All subjects, except one, required some time to readapt following cessation of rotation. Kennedy and

Graybiel concluded that awareness of the Coriolis stimulation was not necessary for adaptation, and exposure to a constant rotation rate of 1 rpm did not handicap persons with greater than average susceptibility to motion sickness in performing the tests conducted during their study.

Studies of longer duration, fourteen days and twelve days, were conducted at 3 rpm and 10 rpm, respectively, to specifically look at the effects of forces which might be created by a rotating spacecraft (Guedry et al., 1962; Graybiel et al., 1965). The only test that showed a reduction in performance during the twelve-day study was the Graybiel-Fregly Posture Test which involved standing and walking. Clinical and psychophysiological tests showed that countermeasures, in addition to adaptation, would be necessary at rotation rates of 10 rpm. While the findings of the Pensacola Slow Rotation Room were significant, it must be kept in mind that the SRR rotated about a vertical axis and subjects stood parallel to the rotation axis, perpendicular to the orientation which would be used in a rotating space vehicle.

Langley Research Center

The rotating-vehicle simulator at Langley Research Center used by Stone and Letko (1962a, 1962b, 1964) required that subjects lie on their back enclosed in a small cabin. Their feet were 15 feet from the center of rotation and the centrifugal force was felt on their feet so as to correctly simulate artificial gravity by rotating about an axis perpendicular to the body's z-axis. Subjects were given simple tasks of monitoring lights of different colors and, when a certain colored light illuminated, placing probes into appropriate receptacles to depress a switch which turned off the light. The task required the subjects to turn their head to the left or right in order to observe the lights. Direction and rate of head motion and the time from illumination to extinguishment were recorded. This type of task represented astronauts monitoring consoles in different locations. All subjects experienced malaise,

and several subjects were unable to complete the experiment because of the high cross-coupled angular accelerations experienced by the sensory organs. Results showed that humans could adapt to turning head movements better than nodding motions, and adaptation did occur even during the combined exposure of nodding and turning motions. Further study was recommended to determine whether head motion could be controlled while maintaining efficiency in performance and while maintaining nausea and illusions of motions below tolerable levels.

Graybiel Laboratory

Lackner and DiZio at Brandeis University's Graybiel Laboratory have been conducting studies on Coriolis force perturbations of arm trajectories (Lackner and DiZio, 1994; DiZio and Lackner, 1995). Testing occurred in a rotating 6.7 m diameter, fully enclosed chamber. Subjects were seated in a chair either at the center of rotation or 1.9 m away. Reaching movements were made in the dark towards a just-extinguished illuminated target located under a horizontal Plexiglas surface at waist level. Movements were timed from the moment subjects let go of the switch which extinguished the light-emitting diode (LED) until they touched the surface above the LED. Trajectories were monitored by a WATSMART motion recording system through an infrared emitter taped to the tip of the subject's index finger. Subjects were rotated counterclockwise at 10 rpm. Those from the on-center group (who experienced 1.0 G) adapted within 10 arm movements while those off-center (who experienced 1.022 G) did not adapt even after 40 reaches. After the cessation of rotation, trajectory errors were made in the opposite direction of those made during rotation. The study showed that both endpoint accuracy and arm trajectory were dependent on the gravitoinertial force level, even with small differences in force backgrounds. Further research was suggested in the area of whether adaptation to certain gravitoinertial levels would transfer to different force levels with identical Coriolis forces. Again, although Lackner and DiZio have gained a better understanding of the movement

control model in Figure 1-2, their experiments were not conducted in the proper orientation with respect to the axis of rotation in order to simulate the force environments within rotating spacecraft.

North American Rotational Test Facility

Studies conducted by the NASA Langley Research Center and North American Rockwell Corporation utilizing the North American Rotational Test Facility were undertaken to clarify the parameters involved in designing manned space vehicles (Piland et al., 1970). Further studies also assessed humans' ability to adapt to a rotating environment (Peacock and Green, 1971). The North American Test Facility was a 24 m radius facility with a living module, capable of supporting four men up to 30 days, located at one end of the facility 23 m from the center of rotation and performance test stations located at the other end at radii of 9 m and 24 m. The facility had the capability of rotating up to 6 rpm and was designed to be able to expand to a 38 m radius for future research.

A research program was developed to investigate crew mobility, cargo transfer and handling, and fine motor coordination in rotating environments with rotation rates up to 5 rpm and radii up to 24 m. Crew mobility tests and cargo handling tests were performed with subjects supported by a sling apparatus to negate most of the effects of the Earth's gravitational field, and to align the subjects' body axes with the artificial gravity vector. A radial elevator was used to test passive radial transport. Psychomotor tests were performed in the living module, at the 9 m and 24 m test stations, and at the nonrotating hub. The various psychomotor tests included the Langley Complex Coordinator (LCC), the Stromberg Dexterity Test, a modified Stromberg Dexterity Test, a pursuit rotor test, and a Decision Response Time test. In addition, ataxia tests were performed so as to relate the degree of ataxia of subjects to their degree of adaptation.

Of most interest to this paper is the use of the Stromberg Dexterity Test and Modified Dexterity Test as performance measures of gross motor tasks. The Stromberg Dexterity Test involved placing colored pegs into correspondingly colored holes, and the Modified Dexterity Test utilized the basic Stromberg task with the device inclined 45° from the horizontal. Both tests were measured by time to completion. Several factors were evaluated, which included rotation rate, fatigue, patterned head movements, and adaptation. A standardized set of head movements was employed to simulate random head movements and determine the effect of forced head movements on performance. The dexterity tests were performed in three orientations: pro-spin (facing the rotation direction), anti-spin (facing against rotation), and radial (facing axially), and the subjects were exposed to rotation rates of 3 rpm, 4 rpm, and 5 rpm. One-day, three-day, and seven-day tests were conducted over the course of twelve days. Subjects experienced an increase in arm fatigue during rotation and committed errors such as dropping pegs, placing pegs in wrong holes, or placing pegs out of sequence. In addition, warm-up trial times were significantly slower than those performed under other conditions. Peacock and Green may have incorrectly assumed that this difference in performance times was related to a decrease in motivation level during the warm-up. It was more likely caused by either the subject's trepidation in practicing the task or an effect of learning. The intention of the study in this paper was to avoid the problems encountered during Peacock and Green's study. Furthermore, the dexterity tests conducted in the North American Rotational Test Facility were not performed with subjects rotating about the proper axis to simulate a rotating space vehicle.

3.0 Experimental Apparatus

The experiments carried out in the current study were performed at the Massachusetts Institute of Technology (MIT) Man-Vehicle Laboratory (MVL). The MIT Artificial Gravity Simulator (MIT-AGS), originally termed the Artificial Gravity Sleeper and constructed in

1987, was rebuilt and modified for this project. In addition, a removable wooden arch, termed the Experiment Arch, was constructed as the apparatus to conduct the performance tests with and was attached to the MIT-AGS at the subject's eye-level.

MIT Artificial Gravity Simulator

The MIT-AGS is a 2 meter radius centrifuge which was originally designed and constructed by Peter Diamandis for his Master's Thesis (Diamandis 1988). Diamandis named it the Artificial Gravity Sleeper (AGS) because he studied whether his subject could obtain a restful sleep while rotating. After his thesis project was completed, the AGS was completely dismantled and pieces were stored wherever room could be found for them. When deciding what apparatus to use for this artificial gravity human performance study, Dawn Hastreiter, another graduate student in the MVL, was looking for a means to conduct an artificial gravity study on human physiology. It was decided that both studies could use Diamandis' AGS if it could be reconstructed. The simulator was modified and rebuilt with the help of Dawn Hastreiter, Dick Perdichizzi, and Don Weiner. It was renamed the MIT Artificial Gravity Simulator since it was no longer used for sleep studies (See Figure 3-1).

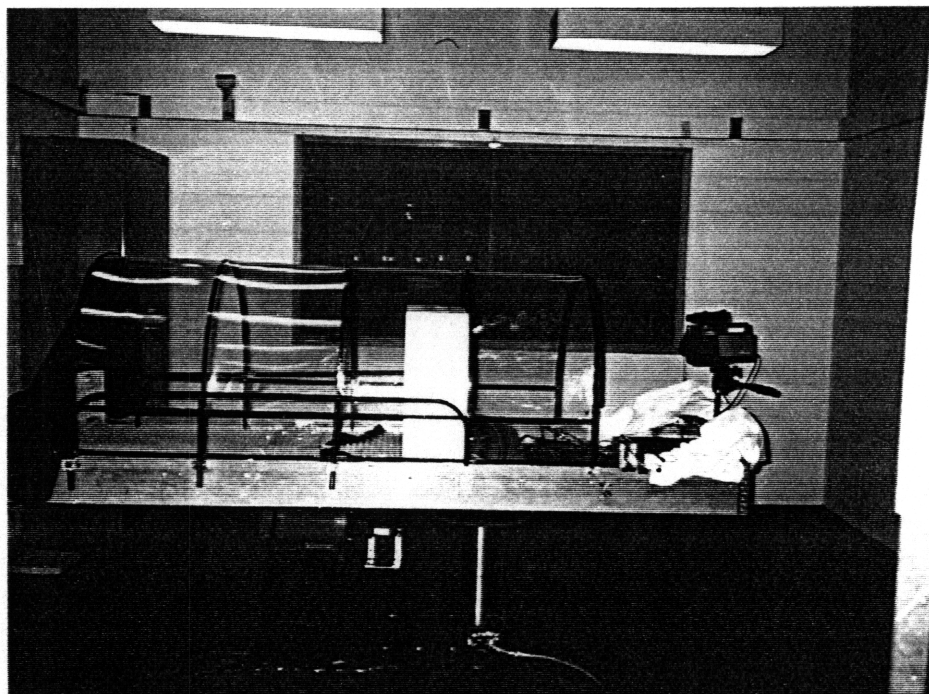


Figure 3-1 MIT-Artificial Gravity Simulator

Many of the original pieces were found, however others had to be bought or redesigned and remanufactured. Most of the pieces of the drive system which rotated the AGS were found and were reusable. The original steel baseplate, gears, gear reducer, central support shaft with bearings, and the Browning 1 hp DC motor were reused. The MIT-AGS baseplate and motor were bolted to the floor of the MVL Sled Room and the drive system was reassembled. A 660H200 Browning Gearbelt was bought from Olmsted- Flint, Inc. (624 Main Street, Cambridge, MA 02139; 617-876-7540), as a replacement, since the original belt was worn. Diamandis' drive system diagram has been duplicated in Figure 3-2.

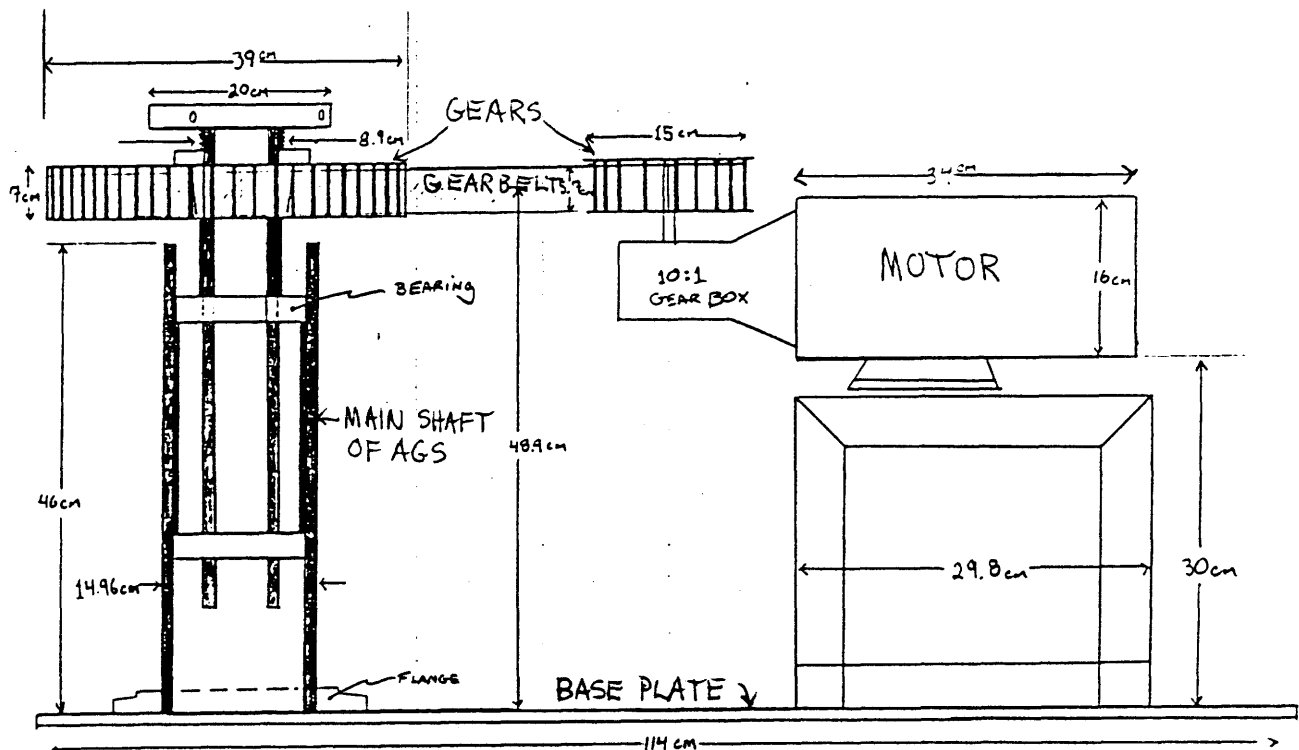


Figure 3-2 AGS Drive System (Diamandis, 1988)

The aluminum honeycomb platform which the subjects laid upon was also salvaged, as well as the side rails and wind canopy. The wind canopy consisted of aluminum strips which Diamandis molded into arches, jointed with aluminum crossbars by nuts and bolts, and then covered by 3M transparent heat shrink plastic.

Modifications Made to the Artificial Gravity Sleeper

As previously mentioned, some additional modifications were made specifically for the new studies to be conducted on the MIT-AGS. The Browning LWS Series (LWS25/200) second generation DC motor controller used to power the AGS was missing. A Focus 2 DC Drive (P/N 2450-8000W) motor controller was purchased to replace it, through Olmsted-Flint, from Control Techniques Drives, Inc. (Grand Island, New York; 606-689-4900) who took over making the motor controllers for Browning motors. The Focus 2 DC Drive was a single phase motor controller for DC motors of 1/4 - 5 hp and required a 240-volt AC power supply. Three option kits were obtained from Control Techniques and added to the new Focus 2 motor controller: a Magnetic Reversing Kit (Part# 2450-9018) which enabled the MIT-AGS to be rotated counterclockwise (in reverse) as well as clockwise, a Dynamic Braking Kit (Part# 2400-9005) which enabled the MIT-AGS to stop rotation within ten seconds in the case of an emergency, and a Voltage Signal Follower (Part# 2450-9012) which enabled the motor controller to be used remotely.

The first major modification made to the AGS was the safety/emergency shut-off system. The old system no longer existed, so a new system was developed, as shown in Figure 3-3. The MIT-AGS safety system included a seat belt and an emergency button which were connected in series to the Start/Stop switch on the motor controller. The seat belt was a conventional quick-release belt with a lifting buckle. One multi-stranded wire was attached to each the buckle and the belt-insert using a screw, shake-proof washer, and nut which were screwed into a lug soldered to the wire and screwed through holes drilled into the buckle and insert. The emergency button was a red, normally closed push-button, and was attached to the other end of one of the wires coming from the seat belt. The wire coming from the other side of the seat belt connection and the other wire coming from the emergency button were attached to the terminals which went through the slip ring. A two-wire cable went from the other end of the slip ring, into the Focus 2 motor controller. A 9-

volt DC four-pole relay (SRU-S-109L; ORIGINAL) was placed inside the motor controller, between the start/stop switch of the motor controller and the safety circuit. The relay was powered by a plug-in class 2 120-volt AC to 9-volt DC transformer (Model# DC905M3; JAMECO) and had a rectifying diode (IN4006) soldered in parallel to its magnetic coil to prevent voltage spikes from being sent back through the safety circuit after the coil had been charged up and the circuit was broken. The MIT-AGS could not start when the safety circuit was open (i.e., if the seat belt was not closed or if the relay was not powered); and, when the circuit was opened (i.e., if the emergency button was pressed or if the seat belt was opened), the dynamic braking system was enabled. Normally, the MIT-AGS would be accelerated and decelerated using the speed potentiometer on the motor controller, and it took 30 seconds to a minute to completely stop rotation. However, when the dynamic braking system was used, the MIT-AGS could be stopped in 10 seconds without moving the speed potentiometer.

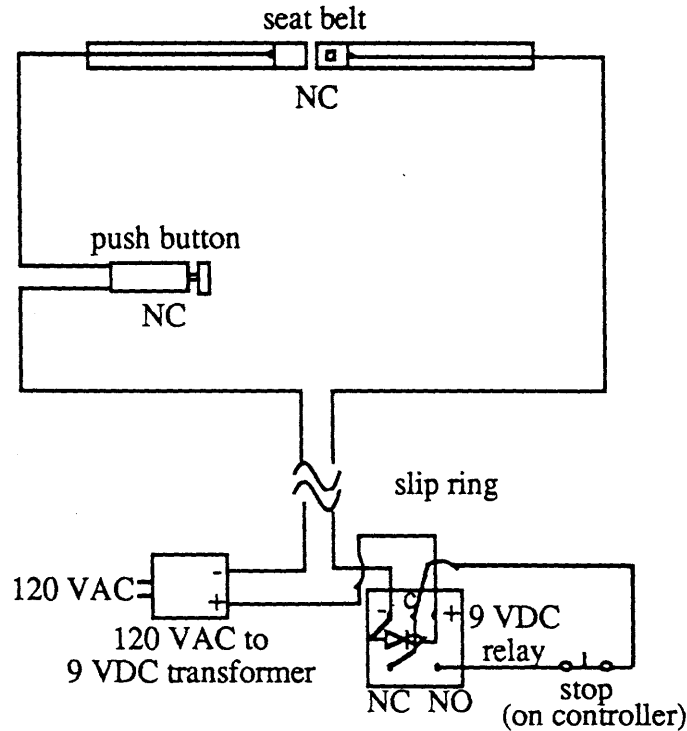


Figure 3-3 Unenergized Safety Circuit

In an attempt to enable the rotation rate of the simulator to be controlled by a computer and to get a more accurate reading of the rotation rate of the MIT-AGS, a DC voltage generator (Model# J36B; Eastern Air Devices, Inc.; Brooklyn, NY) was used as a tachometer. Dawn Hastreiter designed a way to mount the generator to the shaft of the gear reducer in the drive system, as shown in Figure 3-4. Wires from the two leads on the tachometer were attached to a volt-meter (FLUKE 75 Multimeter; John Fluke Mfg. Co., Inc.; Everett, MA). However, the tachometer voltage reading fluctuated frequently and with large enough magnitude to prevent attachment to a computer. In the end, a constant rotation rate was obtained through manual feedback by using a combination of voltage readings, visual timing, and the speed potentiometer setting on the motor controller. Rotation rate was accurately controlled within 1 rpm.

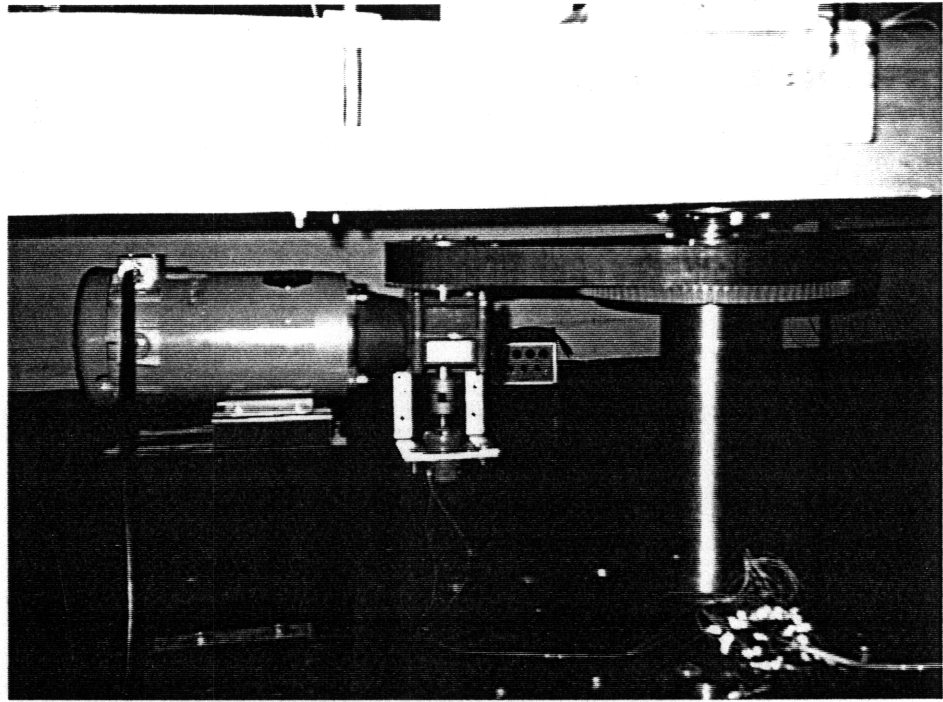


Figure 3-4 MIT-AGS Drive System with Tachometer

In addition, the footplate which provided a “floor” for the subjects was missing and had to be reconstructed. Dawn Hastreiter remade the footplate, as dimensioned in Figure 3-5, from an aluminum rectangular plate and two side angle brackets. The angle brackets helped prevent the plate from unintentionally sliding. In addition, the footplate was attached to grooves along the edge of the MIT-AGS walls by two bolts with washers and nuts. The

position of the footplate was adjusted by sliding the plate to the subject's height and refastening it with the bolts and nuts. The minimum height able to be accommodated was 4 feet 11 inches, and the maximum height accommodatable was 6 feet 5 inches. For comfort, BIO-FOAM™ (BC 2509 Peace'n Quiet™ Mattress Pad; COMFORT CLINIC; Lithia Springs, GA 30057; 1-800-527-FOAM) was placed on the inside of the footplate, as well as on the portion of the platform where subjects lie.

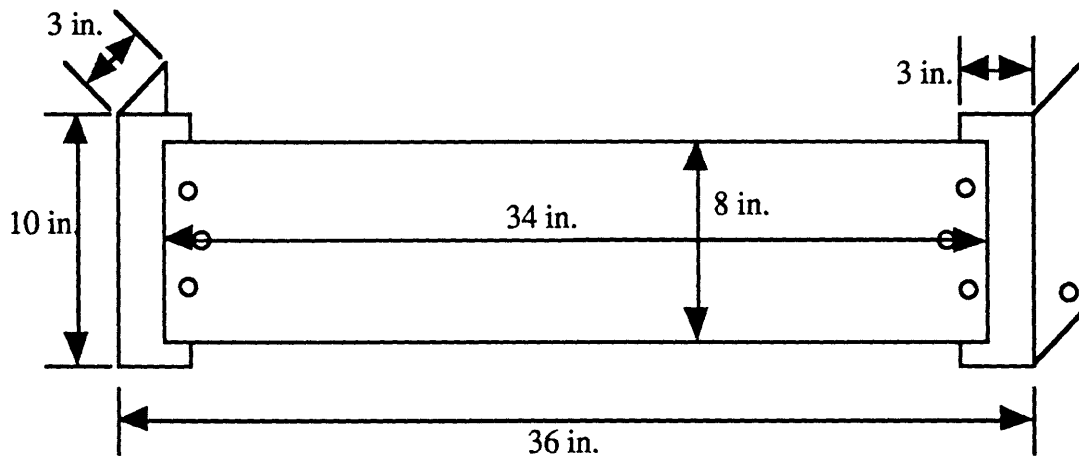


Figure 3-5 Footplate Dimensions

The slip ring system was also missing and had to be redesigned. Another 32 channel slip ring (Part# 1444; Poly-Scientific, 1212 Avenue of the Americas, New York, New York 10036) was used to bring the telemetry wires down the central shaft of the MIT-AGS without tangling them while rotating. An aluminum rod with a 0.5 inch diameter was used to hold the wires and was attached to the shaft of the slip ring with a three degree-of-freedom bearing to prevent wearing of the slip ring cylinder. The slip ring and aluminum rod were placed inside the MIT-AGS's central shaft as shown in Figure 3-6. The rod was press fitted into the center of a circular piece of aluminum placed at the top of the central shaft to hold the rod in place, and the head of the slip ring was screwed into another circular plate at the base of the central shaft. The telemetry wires were brought out through a hole at the base of the central shaft.

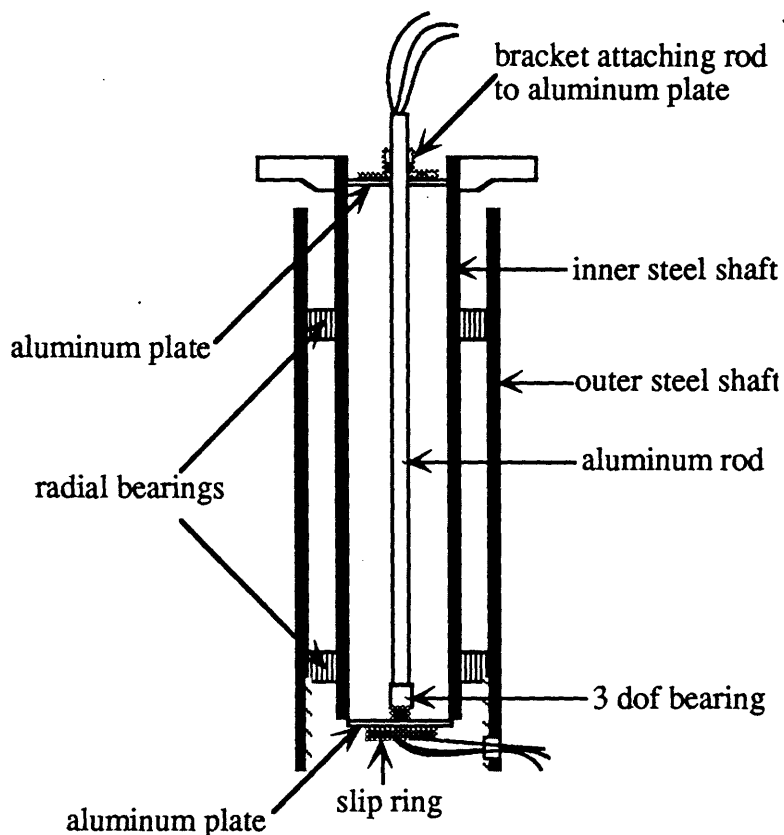


Figure 3-6 Cross-section of Main Shaft to Show Slip Ring System

In order to better monitor the subjects, and to be able to record experiment sessions, a color RCA video camera (Model# CKC019) was mounted to the back wall of the MIT-AGS, at the end behind the subject's head. The camera was mounted using the central piece of an adjustable tripod and chemistry brackets which were screwed onto the back wall of the MIT-AGS around the tripod. The camera setup can be seen in Figure 3-1. The video and audio wires were brought through the slip ring and connected to a RCA video cassette recorder (Model# VMT385) and then channeled into a SONY black and white video monitor (Model# PVM-122). The video monitor had the capability of scanning "under" the normal view of the camera so that more of the periphery could be seen, which was useful for trying to see more of the Experiment Arch. The camera was powered by a 12-volt sealed rechargeable lead-acid battery (Model# NP7-12FR; YUASA-EXIDE, Inc.; Reading, PA 19612) which was placed in the instrumentation section of the MIT-AGS. The

monitoring and recording system was located next to the motor controller, as portrayed in Figure 3-7.



Figure 3-7 Video Monitoring/Recording System

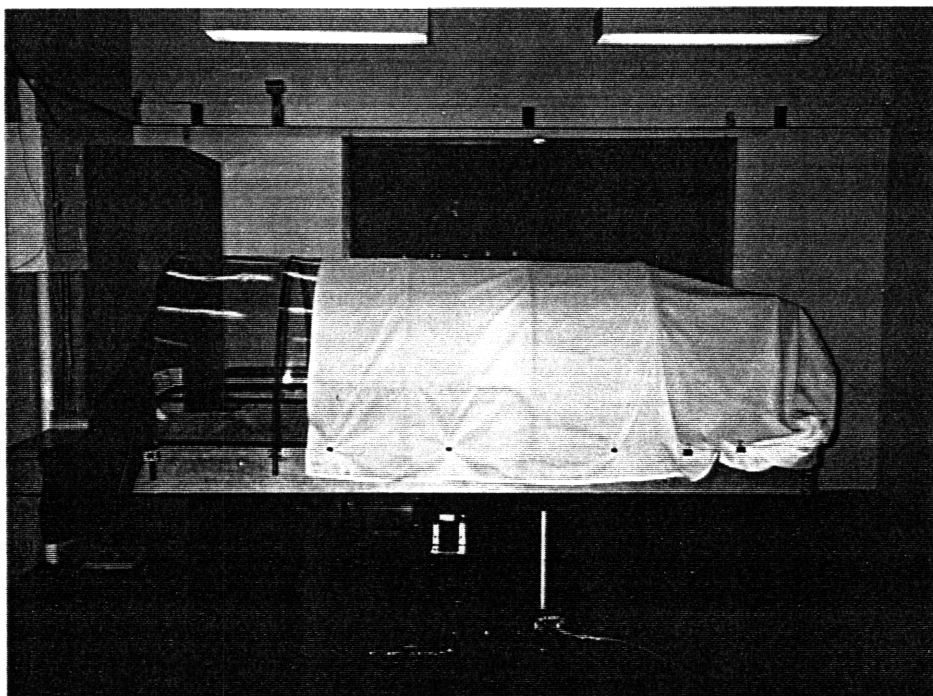


Figure 3-8 MIT-AGS with Sheet to Ameliorate Visual Field

The original black cloth wind shield at the feet was reused and then a white sheet was bought to be dually used as the wind shield by the head and a partial cover over the wind canopy so that the hanging lights did not bother the subjects while being rotated. The black wind shield was attached to the wind canopy by Velcro™, and the white sheet was attached with binder clips (See Figure 3-8).

Experiment Arch

The Experiment Arch, used to conduct performance tests on, was constructed out of pine wood. Alexander Manka, an undergraduate researcher, aided in the final stages of completing the Experiment Arch. The arch consisted of five .75 inch-thick boards which were glued and nailed together according to the design shown in Figure 3-9. The two vertical boards were attached to the MIT-AGS by putting bolts and washers through two holes on each of the side walls of the MIT-AGS and then through Dexion™ strips which were screwed into the bottom of the boards. The arch was placed at the subjects' eye level.

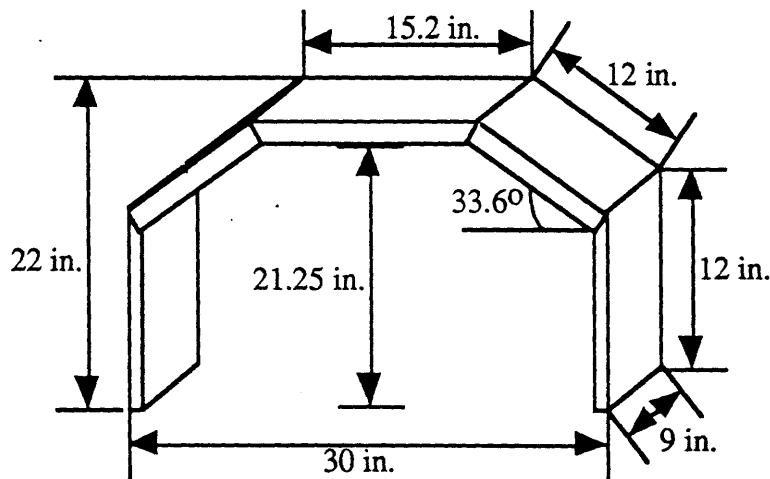


Figure 3-9 Experiment Hood Dimensions

The three top boards contained holes into which cylindrical blocks were placed, 54 in total, with the configuration shown in Figure 3-10. The design of the arch was determined by the limiting dimensions of the MIT-AGS platform and wind canopy, and the requirement of

having all the experiment blocks within the visual field of the subjects as defined by Bailey (1989). It was assumed that the subject's eyes would be 7 inches above the platform. The cylindrical blocks were 1.5 inches in diameter and 1 inch tall. They were spray-painted red, yellow, or blue (eighteen blocks per color). Steel Fender washers with 1.25 inch outer diameters (.25" x 1.25") were glued to the bottom of each block using ZAP-A-GAP CA+ (Pacer Technology; 9420 Santa Anita Ave., Rancho Cucamonga, CA 91730; 714-987-0550) so that round magnets could be used to hold the blocks in place. The magnets used were 3/4 inch diameter ceramic discs (Part# 07003; The Magnet Source; Castle Rock, Colorado). Each of the three top boards had eighteen 1.5 inch diameter holes drilled into them using the MIT Aeronautics and Astronautics Project Laboratory milling machines.

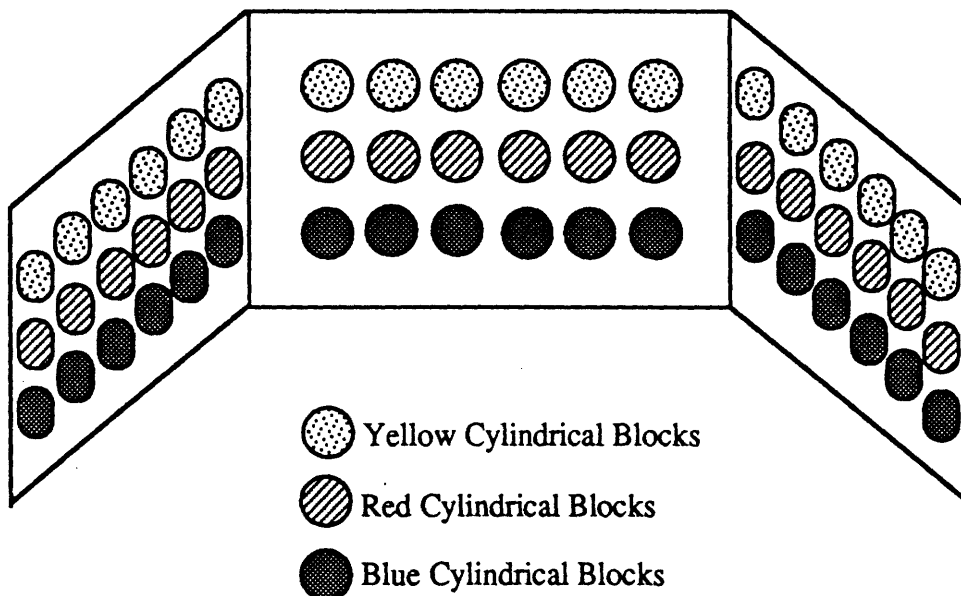


Figure 3-10 Boards With Blocks From View of Supine Subject

The holes on each board were placed in six columns and three rows with their centers 2 inches apart. 3/4 inch diameter holes were drilled within the existing holes for the magnets to be placed. In addition, 1/16 inch holes were drilled into the center of each of the block holes so that wires could be brought in from behind the boards. Two wires were brought into each hole, connected in series with each other, and glued into place under the magnets

using ZAP-A-GAP, so that a circuit would be completed when all the blocks from a board were in their holes and the washers were touching the two wires.

Potentially, trials could be timed by a computer from the moment any circuit board was opened until the last moment all circuits were closed. However, complications arose involving dropped blocks and not putting the blocks in completely flush. Since the board circuits only closed if all the blocks were completely flush, it was decided that manual timing with a Micronta LCD quartz stopwatch was preferable at this time in order to avoid losing data.



Figure 3-11 Subject on MIT-AGS Looking Up at Experiment Arch

4.0 Experiments

Experiment Design

Twelve subjects, six male and six female, participated in this study.. All subjects were MIT students between the ages of 20 and 30. None had any conditions which would have prevented them from having full use of their arms and hands. In addition, all had

correctable vision to 20/20, and none disliked spinning. The subject selection questionnaire can be found in Appendix B.

A modified Stromberg Dexterity Test was used as the performance test and was measured by time to completion. The original Stromberg Dexterity Test was designed to aid in the selection of workers for jobs requiring speed and accuracy in hand movements, and it was used by Peacock and Green in their performance studies because of its susceptibility to Coriolis forces (Peacock and Green, 1971). The Stromberg Dexterity Test was performed standing up, and required the subjects to place 54 cylindrical blocks of three different colors into correspondingly colored holes. The blocks were moved from horizontal rows of holes to vertical columns. The modified test used in this study was performed supine and involved using both hands to simultaneously exchange the position of two blocks located in an arch in front of them until all the blocks in the sequence were moved.

Two sequences were used which involved making arm movements in different directions perpendicular to the axis of rotation. Sequence A contained 27 block exchanges while Sequence B contained 18 exchanges. Sequence A required subjects to start at the bottom levels of the two side boards and exchange the blocks from the two sides with their mirror image. Execution of the task necessitated simultaneous movement of the arms in opposite directions. For example, the lowest yellow block on the right side was exchanged with the lowest yellow block on the left side. Each block on a level was exchanged before proceeding to the next level. Therefore, the subjects exchanged the yellow, then the red, then the blue blocks on the first level and proceeded to exchange the yellow, red, and blue blocks on the second level, and so on. Subjects proceeded up the levels until their hands met when they reached the center of the top board. Sequence A took about a minute to complete, the order of exchanges is depicted in Figure 4-1.

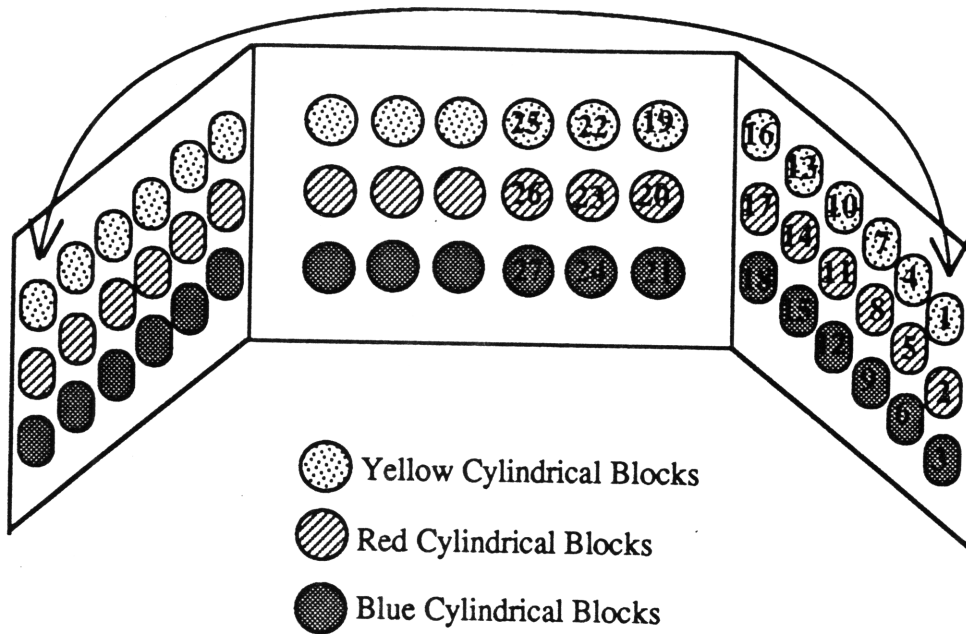


Figure 4-1 Sequence A Block Exchanges

Sequence B required subjects to start on the bottom right level of blocks and exchange the yellow and blue blocks within each level. The subjects went up the right board, across the top board, and down the left board as shown in Figure 4-2. Sequence B took about 30 seconds to complete, half as long as Sequence A.

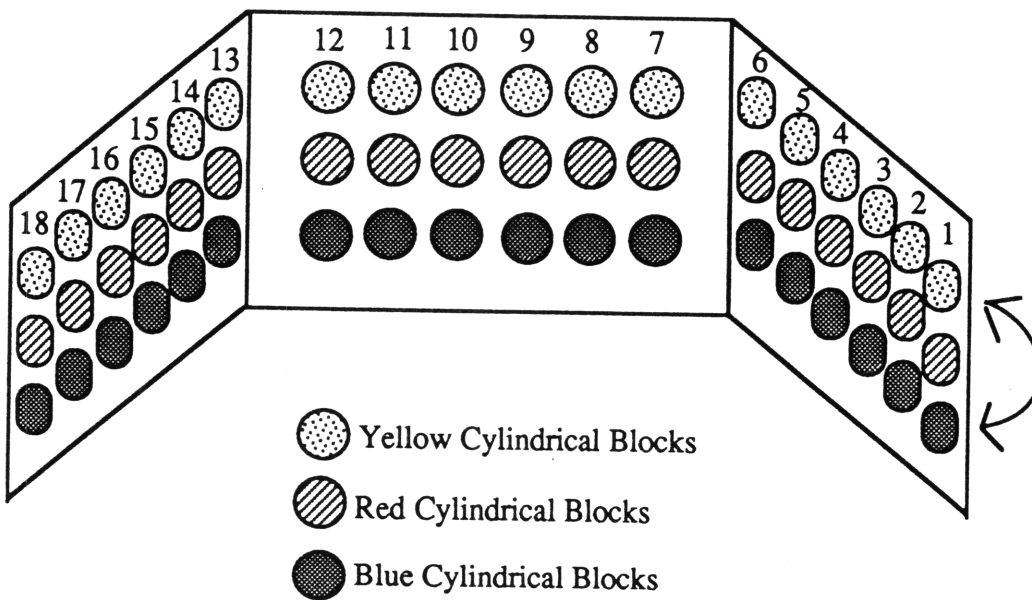


Figure 4-2 Sequence B Block Exchanges

Subjects were split into two groups. They were paired up according to gender, age, and similar stature. One person from each pair was randomly placed in Group 1 or Group 2 and the other subject from the pair was assigned to the other group. During the experiment sessions, subjects in Group 1 performed Sequence A and Sequence B in the following order: ABBAAB. Subject in Group 2 performed Sequence A and Sequence B in a complementary order: BAABBA.

Experimental Procedure

Subjects' height and weight were measured prior to beginning. These measurements were used on subsequent testing days. The footplate was adjusted according to the subject's height so that the top of the subject's head would be at the center of rotation, and his feet would be flat against the foot plate. The appropriate weights were then added to MIT-AGS to counterbalance the subject just prior to him climbing aboard the simulator. Preliminary static trials were performed, during a training session, to assess the subjects' learning curve for each sequence. Preliminary trials are required since subjects naturally improve in their performance of a certain task logarithmically each time they perform that specific task. The purpose of the training session was to reach the asymptotic level of performance, before conducting the main experiments, so that the effect of Coriolis forces could be differentiated from any learning process. There was still a learning curve present over the test days, however. Subjects were instructed to perform the sequences as fast as they could without dropping blocks or putting them in the wrong place. Higher performance was indicated by shorter times to completion of trials. Since Peacock and Green (1971) noticed that errors were hard to recover from, subjects were also instructed to not recover fallen blocks but to rather keep on going. A box with extra blocks was taped to the experiment arch at the subject's right in case some blocks were not recoverable at the end of a sequence (i.e., the block could not be found, its washer fell off, or (for perrotation sessions) it could not be recovered without the subject moving his head). Each of the

subsequent test days involved performing four sessions, a practice session followed by one experimental session before, during, and after rotation.

The perrotation sessions were conducted at a clockwise rotation rate of 20 rpm and the subject and experimenter were in constant communication through the use of voice actuated FM transceivers (Model# TRC-506; Cat.# 21-406; Radio Shack). It was not desired to have subjects become nauseous as during Stone and Letko's experiments (1962a, 1962b, 1964), so it was decided to further look at the ability of subjects to perform tasks with limited head motion. To prevent Coriolis and cross-coupling stimulation of the otolith organs and the semicircular canals while rotating, subjects were asked not to move their head while performing any of the sessions. The centripetal force felt at the feet would be .75G for a 5'6" subject. While exchanging blocks, the Coriolis forces at the arms ranged from 0.06G-0.8G depending on how fast and how far the subject moved his arms.

Each session, except the training session, involved 3 trials of Sequence A and 3 trials of Sequence B in the order dictated by which group the subjects were in. To avoid the fatigue problem encountered by Peacock and Green (1971), rest periods of 1 minute were given after the completion of each Sequence A, and a 30 second rest period was given after Sequence B (approximately equal to the length of each sequence). During the perrotation session, rotation continued during the rest periods. In order to look at adaptation to the artificial gravity environment, the subjects were asked to perform the same practice and experimental sessions on the third day following the initial testing day, and again five days after the test day. The three days of experiments are referred to as Day 1, Day 2, and Day 3. Training was conducted the day before Day 1 and consisted of 9 trials of Sequence A along with 9 trials of Sequence B performed in an extended order dictated by the subject's group (i.e., Group 1's training order was ABBAABBAABBAABBAAB and Group 2's training order was the complement of Group 1's). The sequences were timed by the

experimenter with a stop watch, and all sessions were videotaped for reviewing later. The protocol undertaken when running the MIT-AGS can be found in Appendix C. Instructions read to subjects before the training and three experimental days can be found in Appendix D.

5.0 Results

Data and Observations

The data consisted of numerical output of experiments and the answers to qualitative questions asked of subjects upon finishing their sessions. The numerical data were times each subject took to complete each trial and the number of blocks he/she dropped during it. Those numbers were recorded by the experimenter while the trials were being performed. Whenever an error in timing was suspected, the sequence in question was retimed by playing back the videotape of the session. Since subjects were instructed to go as fast they could without making errors, shorter trial times corresponded to better performance. The data were analyzed through repeated measures analysis of variance.

In certain instances, subjects missed an exchange of blocks or repeated exchanges. Occasionally, one of the magnets that held the blocks in place or one of the washers glued to the blocks would fall off, causing the block to be lost and delaying the subject. Although subjects were instructed to proceed even if blocks fell, they often paused, involuntarily. Some tried, reflexively, to recover the falling block instead of continuing as instructed. These trials were all retimed by video and extra time caused by delays which were not the subject's fault, as when a washer or magnet fell, and extra time taken when exchanges were repeated, were subtracted from the time originally recorded. If a subject missed an exchange, an average of the time taken to make the exchanges preceding and following that exchange was added to the time originally recorded in order to replace the missing exchange. Times so adjusted represented the same number of exchanges, without

distractions. The adjusted training curves created after retiming resembled the exponential curves expected during learning more closely than did the original unadjusted curves (See Figure 5-1 and Figure 5-2). The remaining training curves are in Appendix E. Three invalid trials, in which subjects did not follow instructions properly, were discarded: the first two trials of Sequence A from Subject A's training session, and a trial from Subject H's training session.

Subjects often dropped blocks throughout all the sessions, static and rotating. Scatter plots of trial times versus the number of dropped blocks showed no significant correlation between the number of blocks dropped and performance time (Plots omitted). Most often the blocks were knocked down rather than dropped. Subjects would hit them when exchanging other blocks in the vicinity. Not only did subjects instinctively try to catch blocks, but they adjusted blocks that were crooked so that they would not be easily knocked down. Sometimes it was hard to distinguish between times when subjects adjusted crooked blocks and those times when they recovered those that they knocked. Any adjustment of blocks was considered an error and therefore a "drop".

Subjects' arms fatigued over the course of the experiment, but they reported that the rests in between trials helped. A few subjects mentioned that their arms fatigued faster when rotating while others mentioned the Coriolis forces helped them move faster when performing Sequence B, especially when translating across the top board. In general, subjects moved fastest when working on the top board in front of them: in Sequence A distances between exchanges were smaller and in Sequence B one of the Coriolis vectors pointed in the direction of motion across the arch. Subjects never reached directly up to the top board, in which motion they would feel no Coriolis forces. Therefore, all their motions were subject to Coriolis forces. Another interesting artifact of rotation mentioned by

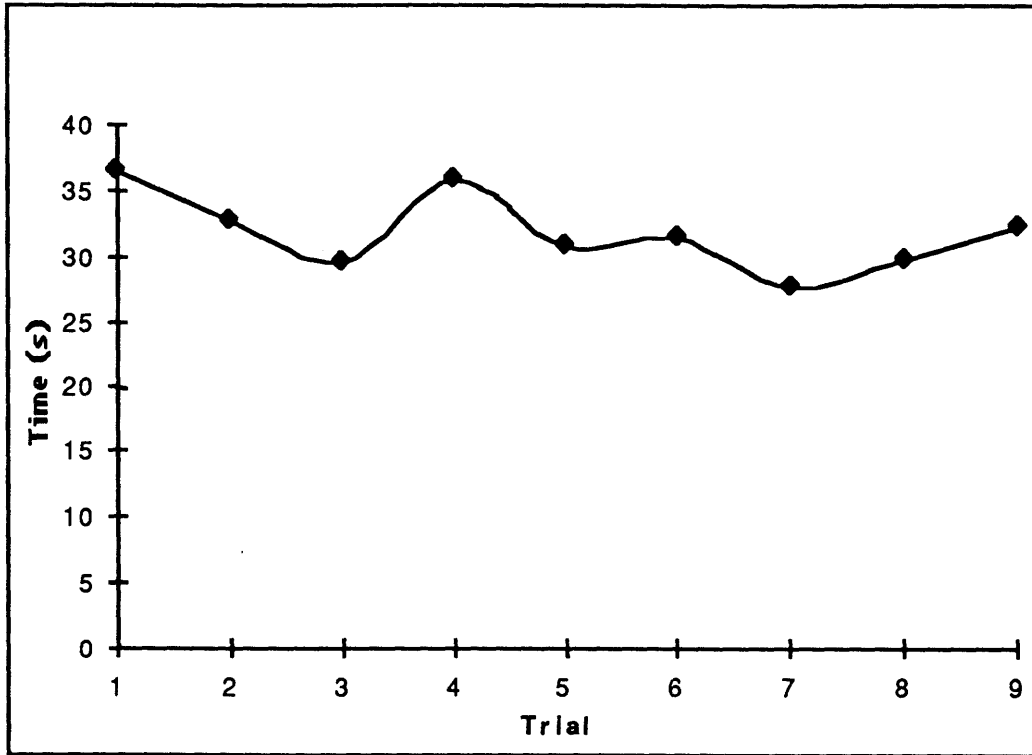


Figure 5-1 Original Training Curve for Subject B, Sequence B

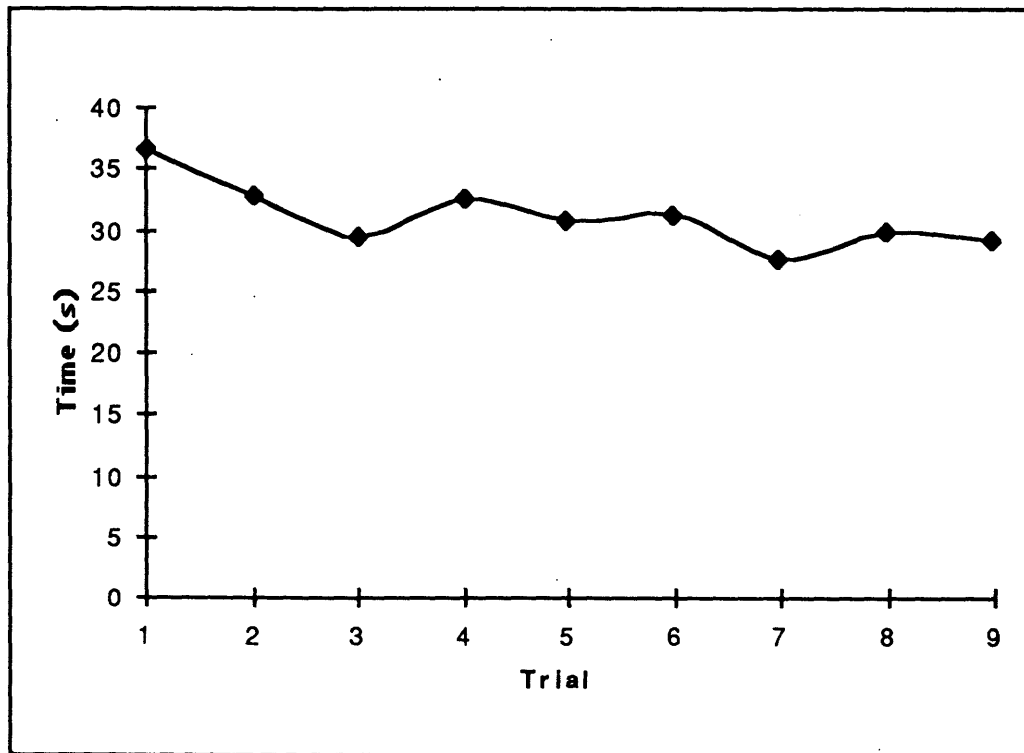


Figure 5-2 Adjusted Training Curve for Subject B, Sequence B

some subjects was that their arms felt lighter while rotating and, therefore, they did not feel the soreness of their arms. When rotation stopped, their arms felt even heavier.

At the beginning of perrotation sessions, subjects immediately noticed the Coriolis forces. More Coriolis forces were felt while performing Sequence A than Sequence B since Sequence A contained side to side motions over longer distances. They noticed that when rotating they reached too high or too low for the holes and tried to “put their hands through each other.” The subjects also reported that adaptation to the rotating and nonrotating environments occurred after the first trial of each sequence type. For some, adaptation occurred “immediately” for Sequence B. This is surprisingly fast adaptation.

Statistical Analysis

The factors analyzed in this study were day (three days of rotation per subject), experimental condition/session (practice, prerotation, perrotation, and postrotation), sequences (two tasks), and repetitions (three per sequence). This totaled 72 measures which were included in the repeated measures model. Training data were not included in this model because subjects completed the training session only once. Because SYSTAT, the statistical software, could not handle 72 repeated measures, the data set was split in two by sequence.

In this protocol, Task (Sequence) A was sometimes followed by another trial of Task A, and sometimes by Task B. The preparatory effect of a sequence is defined as the reduction in time to completion that is observed from practicing the same sequence in the immediately preceding trial. That is, Preparatory Effect of A = $\text{Time}(\text{BA}) - \text{Time}(\text{AA})$ while Preparatory Effect of B = $\text{Time}(\text{AB}) - \text{Time}(\text{BA})$, where BA denotes trials in which Sequence A followed a trial of Sequence B, AB denotes trials in which Sequence B followed Sequence A, and so on.

At the next level of analysis, the two preparatory effects were compared to see which sequence (A or B) benefited more from preparation. It was found that the preparatory effect of A was significant only during training and that of B only during rotation. The difference between the two preparatory effects in any single condition was not significant, as tested with t-tests paired by subject. This suggests that subjects were fully trained in both sequences (See Figure 5-3).

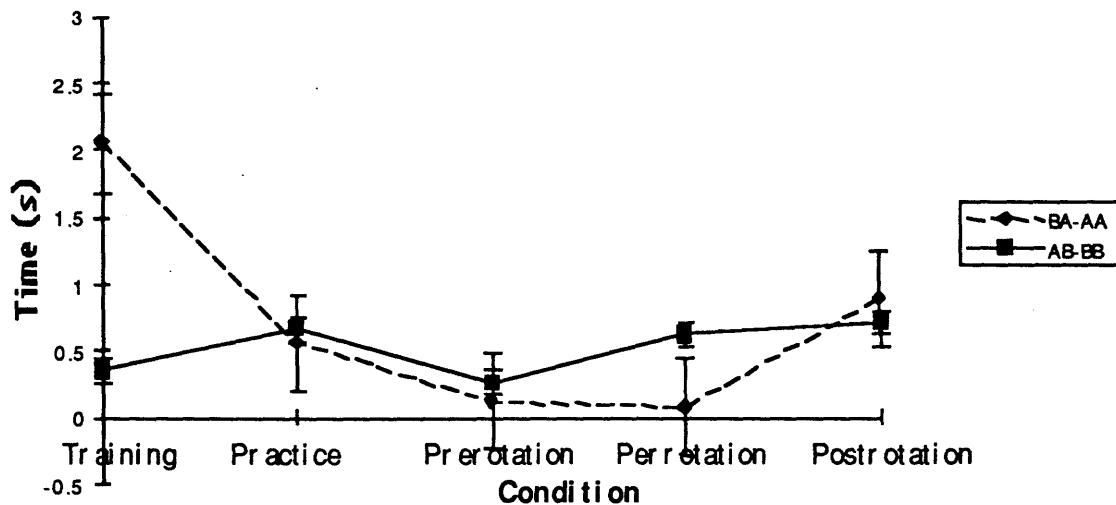


Figure 5-3 Preparatory Effect on A and B Within Subjects

There were no significant effects of gender or of experimental group (Group 1 versus Group 2) for either sequence. The “group” factor was defined by the slightly different orders in which sequences were performed.

A plot of all of each subject’s trial times, in temporal order, was drawn for each sequence (A, B). An example is shown in Figure 5-4 with Subject E’s Sequence A data.

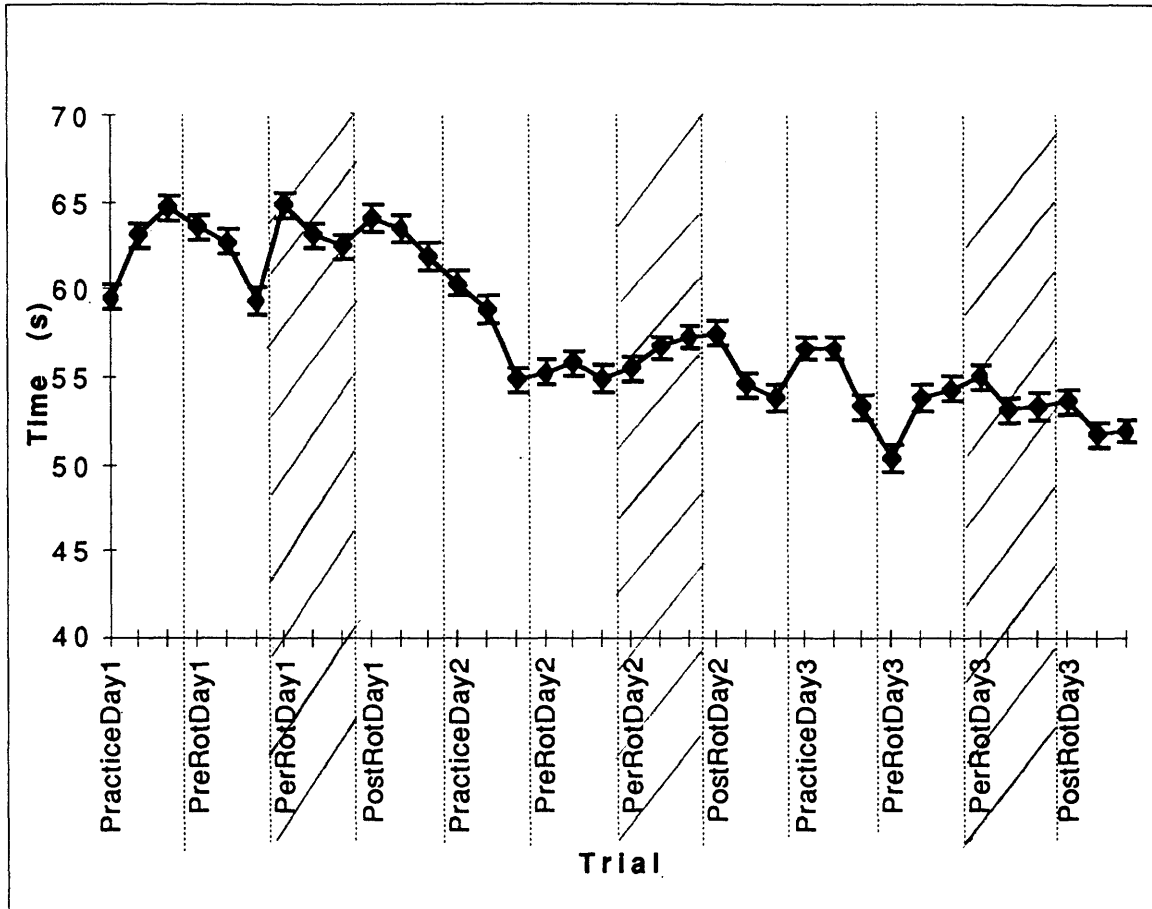


Figure 5-4 Subject E Trial Times for Sequence A in Temporal Order

The vertical lines in Figure 5-4 separate the different experimental conditions. The data points for repetition 1, 2, and 3 of each condition are plotted in chronological order. The perrotation session for each day has been highlighted.

To compare the shape of subject trial time plots, each subject's plot was normalized to 0-mean and unit standard deviation. Subject E's normalized plot for Sequence A is shown in Figure 5-5. The format is the same as that for Figure 5-4. The remainder of the subjects' normalized plots are in Appendix F. There were no obvious outliers, by shape. Performance times generally improved from day to day for both sequences and worsened during the first perrotation and postrotation trials of each day.

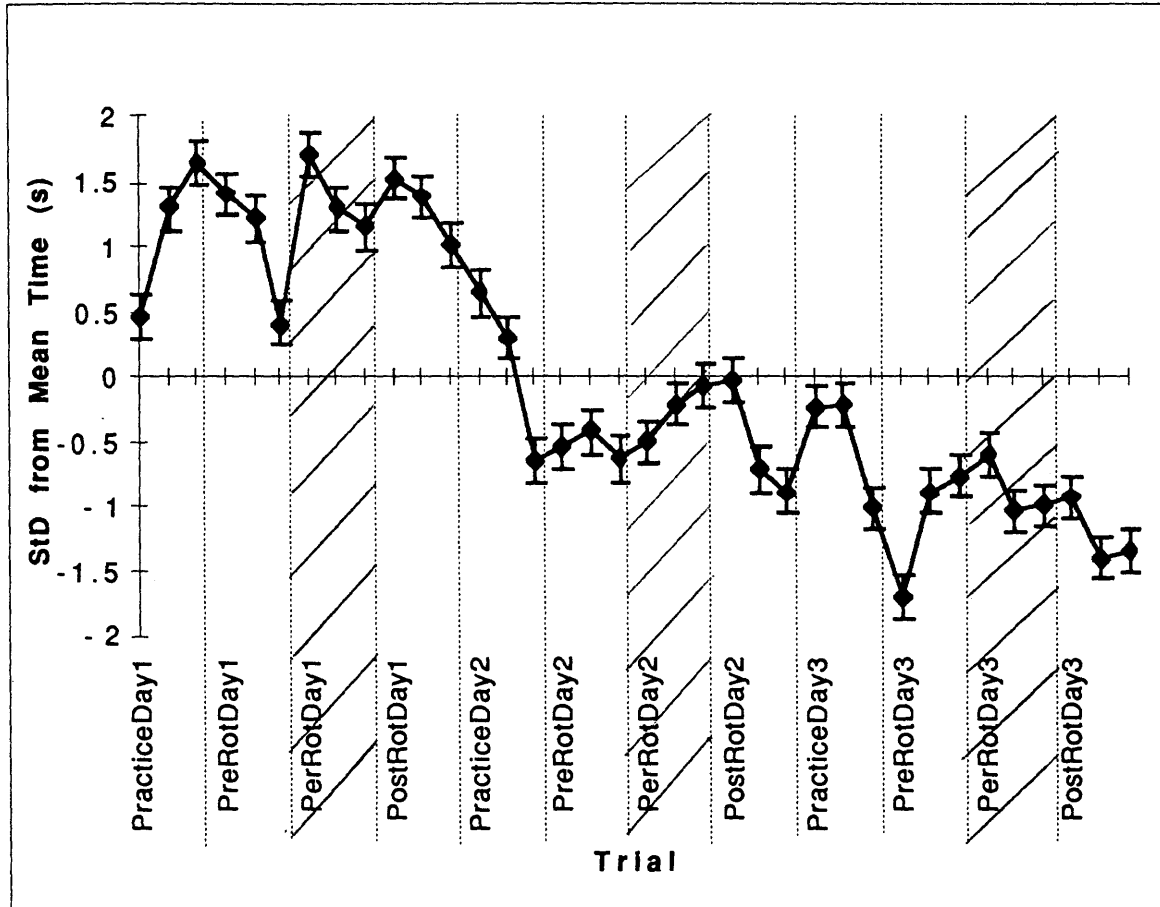


Figure 5-5 Subject E Normalized Trials for Sequence A in Temporal Order

A repeated measures model with contrasts within subjects was calculated. Significant factors were measured by the Huynh-Feldt (H-F) probability, which is a more conservative p-value that takes into account when variances of differences between pairs of trials are not homogeneous. For Sequence A, the significant factors were day, condition, trial repetition, and the interactions condition*repetition and day*condition*repetition ($p < 0.05$). An example of the results produced from the univariate repeated measures analysis is displayed in Table 5-1 with the significant factors for Sequence A. The H-F corrected p-values were not very different from the uncorrected values which suggests that the analysis is valid and that the estimates of the probabilities are reliable. For Sequence B, the significant factors were only day, condition, and repetition ($p < 0.0001$, 0.0010 , and 0.0001 , respectively).

Table 5-1 Significant Seq A Univariate Repeated Measures Analysis Results

SOURCE	SS	DF	MS	F	P	H-F
DAY	2132.4605	2	1066.2302	34.0123	0.0001	0.0001
ERROR	689.6636	22	31.3483			
COND	350.6445	3	116.8815	10.9014	0.0001	0.0006
ERROR	353.8163	33	10.7217			
REP	228.6262	2	114.3131	35.1534	0.0001	0.0001
ERROR	71.5403	22	3.2518			
COND*REP	151.6426	6	25.2738	5.7677	0.0001	0.0004
ERROR	289.2061	66	4.3819			
DAY*COND*REP	87.6007	12	7.3001	1.9350	0.0355	0.0366
ERROR	497.9939	132	3.7727			

All three days were significantly different from one another for Sequence A, but only Day 1 and Day 2 were significantly different for Sequence B. All three trial repetitions were significant from one another for Sequence A, but only Repetition 1 and Repetition 2 were significantly different for Sequence B. Only the conditions practice and prerotation were different for both Sequence A and B, which was surprising since an effect of rotation was expected. (See Table 5-2)

Table 5-2 H-F p-values for Contrasts Between Factor Levels

Contrast	Sequence A	Sequence B
Day 1 - Day 2	p = 0.0031	p = 0.0012
Day 2 - Day 3	p = 0.0003	p = 0.1615
Repetition 1 - Repetition 2	p = 0.0020	p = 0.0005
Repetition 2 - Repetition 3	p = 0.0052	p = 0.1566
Practice - Prerotation	p = 0.0001	p = 0.0025
Prerotation - Perrotation	p = 0.5087	p = 0.1698
Perrotation - Postrotation	p = 0.0795	p = 0.2308

Although test (i.e., excluding practice) conditions generally did not differ overall, there was a significant difference between the first trial and the last two trials within the practice and

test, except for prerotation, conditions. This was indicated by a significant repeated measures contrast between the first trial of perrotation and the mean of the last two. The corresponding contrasts for practice, perrotation, and postrotation were significant while that for prerotation was not, for both Sequence A and B (See Table 5-3). The absence of changes between early and late pre-, and their presence between early and late per- and postrotation trials suggests that the change of Coriolis regimen from the previous condition caused the observed decrease in performance, to be described later.

Table 5-3 H-F p-values for Contrasts Between First and Last Two Trials

Contrast	Sequence A	Sequence B
Practice 1 - (1/2)(Practice 2 + Practice 3)	p = 0.0003	p = 0.0130
Prerotation 1 - (1/2)(Prerotation 2 + Prerotation 3)	p = 0.4983	p = 0.0671
Perrotation 1 - (1/2)(Perrotation 2 + Perrotation 3)	p = 0.0011	p = 0.0006
Postrotation 1 - (1/2)(Postrotation 2 + Postrotation 3)	p = 0.0209	p = 0.0018

The significant contrasts between early (Repetition 1) and late trials (Repetitions 2 & 3) within per- and postrotation conditions suggest that performance may have been affected by the Coriolis forces, but that subjects adapted quickly to the transition between rotating and nonrotating environments (See Table 5-4). The contrasts between the third repetition of pre-, per- rotation and the first repetition of per-, post- rotation, respectively, were significant for both Sequence A and B. That is, there was a significant decrease in performance at both onset and cessation of rotation. The control contrast— between practice and prerotation—was not significant, supporting the view that it was the change in rotation regime that led to the decrease in performance.

Table 5-4 H-F p-values for Contrasts Between Last and First Trials of Consecutive Sessions

Contrast	Sequence A	Sequence B
Practice 3 - Prerotation 1	p = 0.1985	p = 0.6414
Prerotation 3 - Perrotation 1	p = 0.0115	p = 0.0002
Perrotation 3 - Postrotation 1	p = 0.0208	p = 0.0249

6.0 Conclusions

The null hypothesis was that the performance times were the same for all test conditions. The results did not reject it (See Figure 6-1 and Figure 6-2). There was a significant improvement in performance between practice and prerotation sessions, but no significant difference between pre-, per-, and postrotation sessions. Nevertheless, the first trials of perrotation and postrotation sessions showed a significant decrease in performance as against the consistent trend of the immediately preceding trials of pre- and perrotation, respectively (See Figure 5-4).

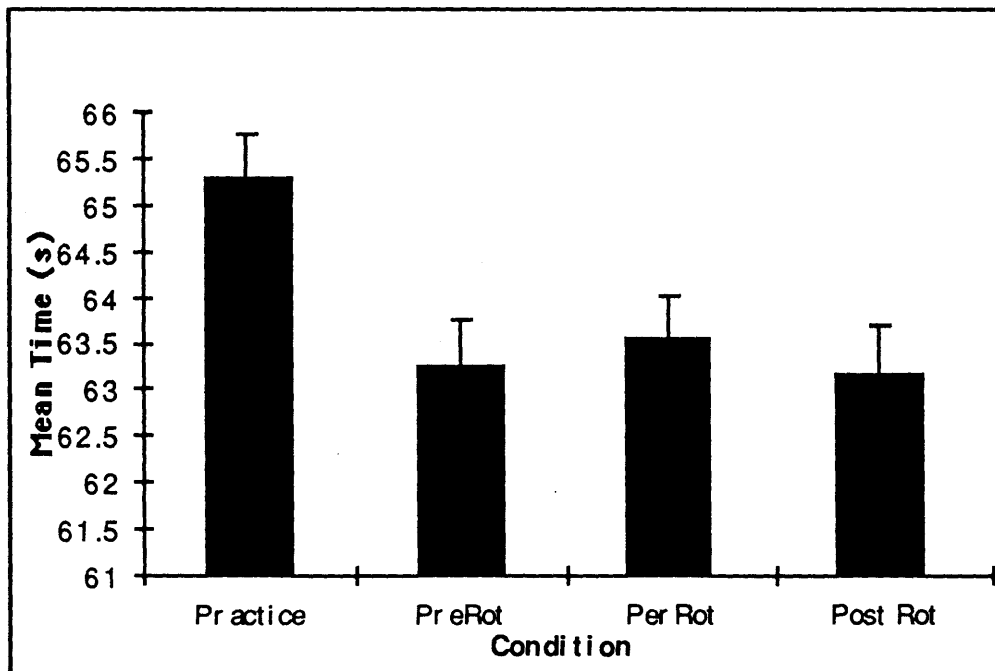


Figure 6-1 Sequence A Mean Times Per Condition Averaged Over Subjects

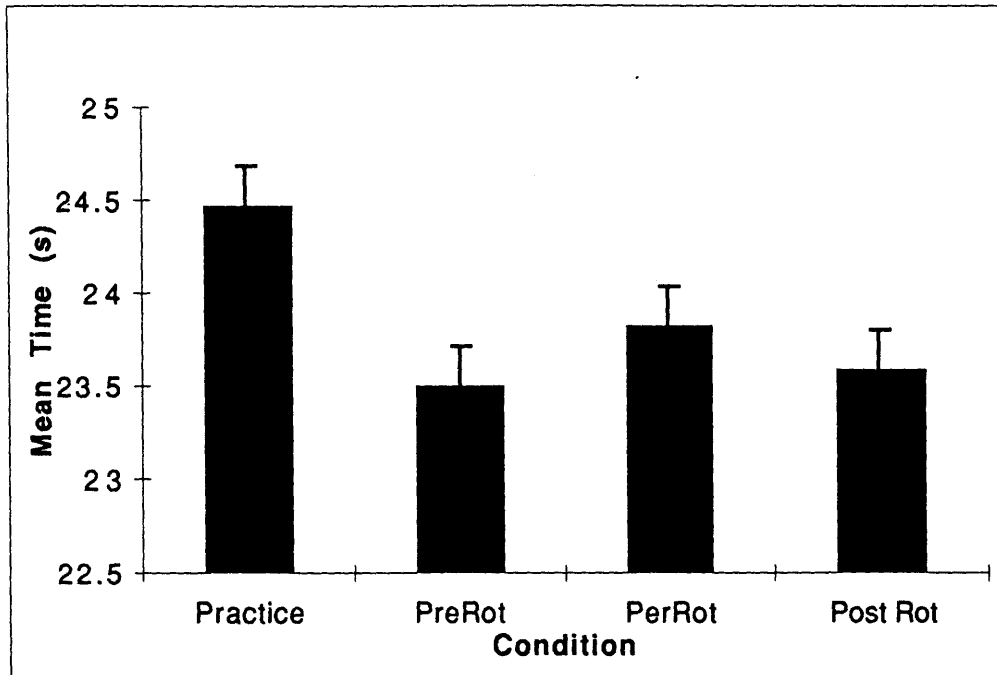


Figure 6-2 Sequence B Mean Times Per Condition Averaged Over Subjects

Two other questions investigated by this study were: 1) Can subjects adapt to Coriolis forces while performing complex two-handed tasks? 2) Would such adaptation result in increases in performance on subsequent days under the same conditions? Although no such decrease in performance due to rotation, presumably due to Coriolis forces, was found, performance did, in fact, decrease at first and then increase during the perrotation and postrotation sessions. That is, the subjects did adapt to the rotating environment and readapt to the nonrotating environment.

In answer to the second question, subjects improved continuously from day to day when performing Sequence A and had to relearn the task each day, as evident from the decrease in performance time between prerotation and practice sessions (See Figure 6-3). The simpler Sequence B evidently required less practice since there was no significant increase in performance between Day 1 and Day 2 (See Figure 6-4). The motions of Sequence B induced smaller Coriolis forces, which may explain the plateau in performance on Day 2. The reduced burden resulting from the smaller Coriolis forces may explain why the

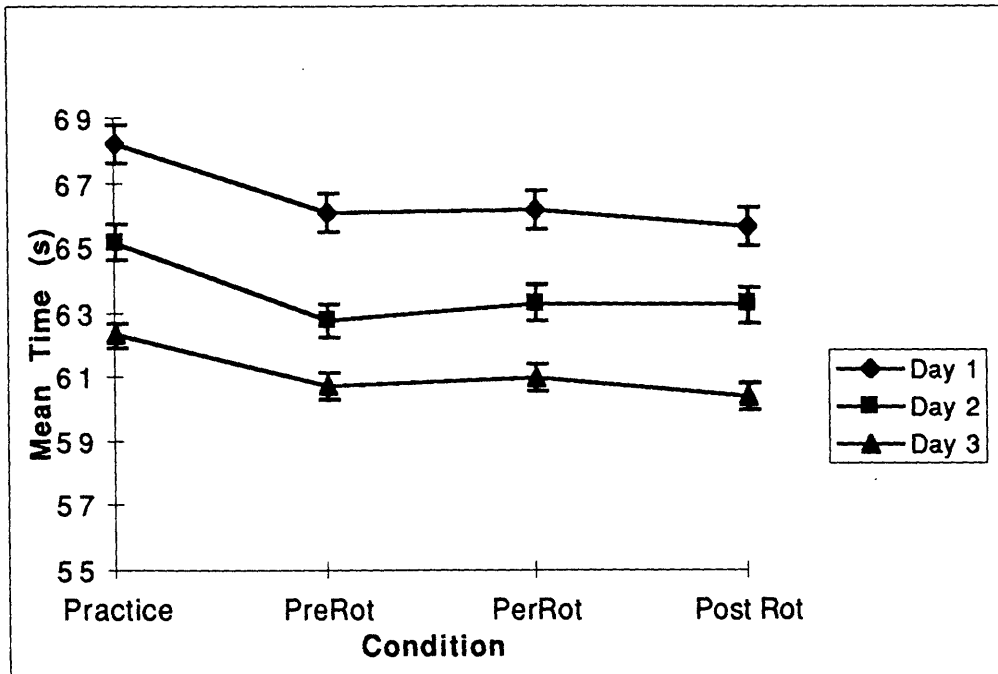


Figure 6-3 Sequence A Mean Times Per Day Averaged Over All Subjects

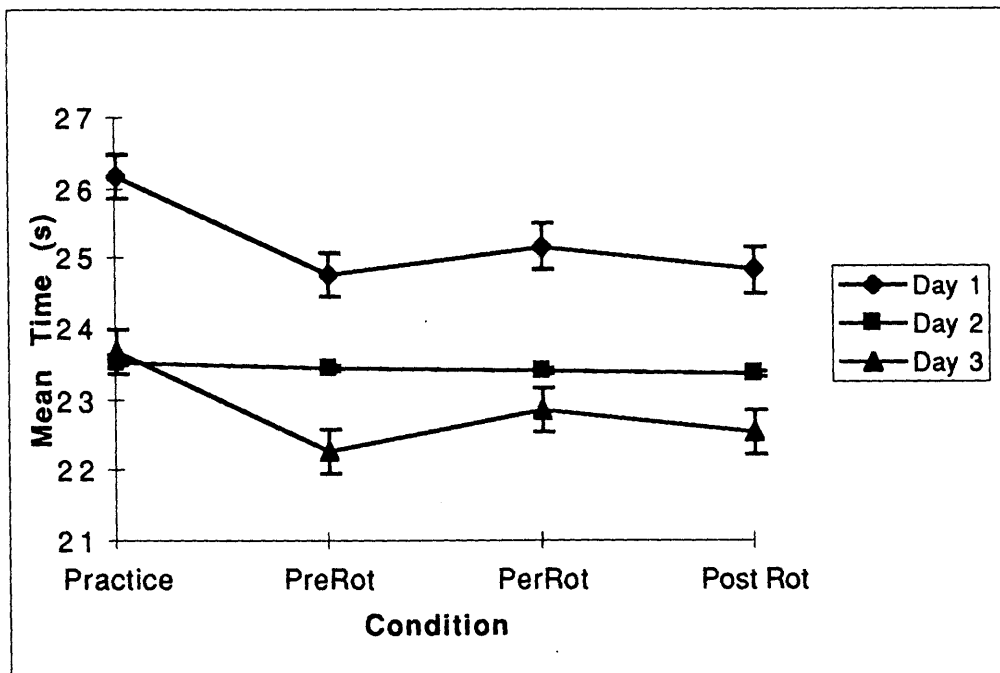


Figure 6-4 Sequence B Mean Times Per Day Averaged Over All Subjects

subjects achieved proficiency in Sequence B with less practice than was required by Sequence A (whose Coriolis forces were more prominent). These two tasks, differing in

component motions, differed also in the time courses of their adaptation, and in the manner expected.

The overall conclusions are illustrated in Figure 6-5 and Figure 6-5, which follow the format of Figure 5-4 and Figure 5-5. These figures show the learning curve over the

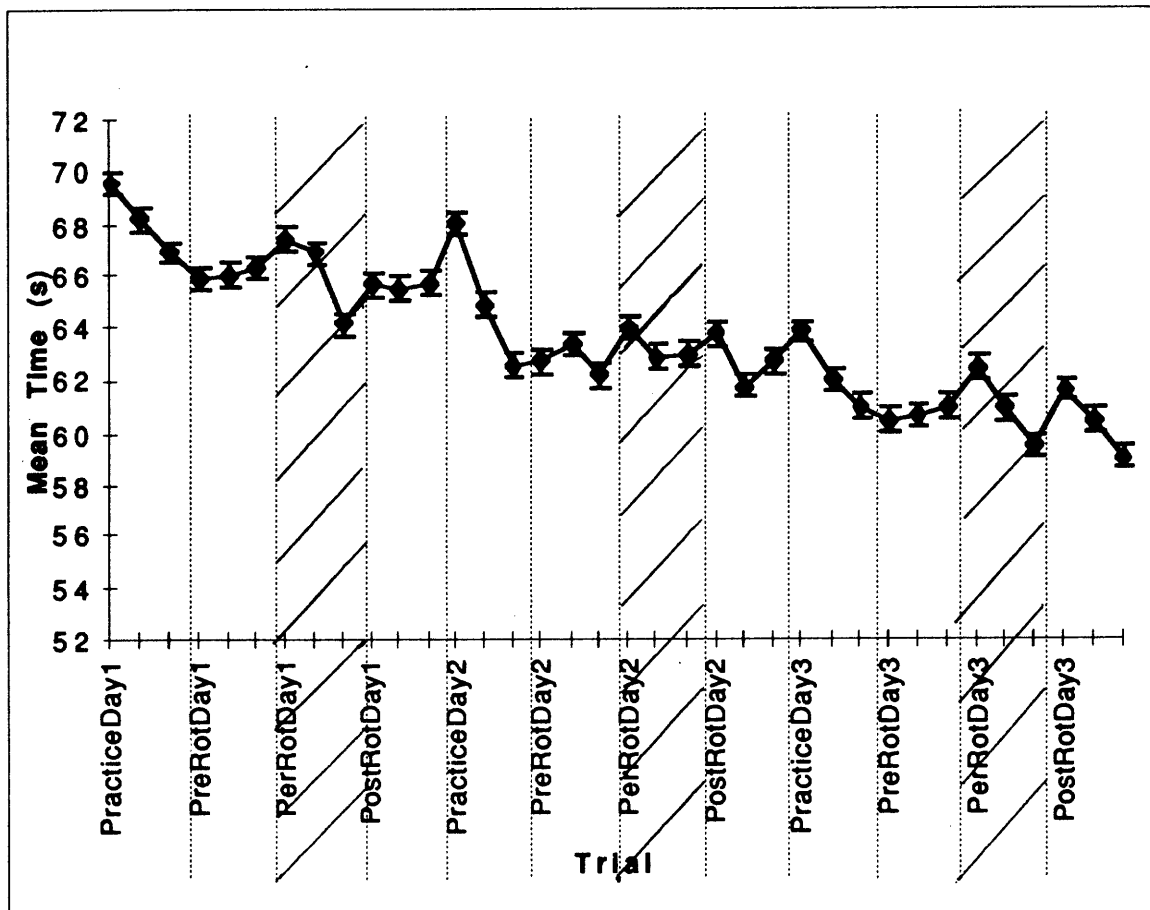


Figure 6-5 Mean Times for Sequence A Trials Averaged Over All Subjects

course of the experiment, whereas that for Sequence B was less dramatic than for A. Performance improved during practice sessions prior to the baseline (perotation) session. There was no significant improvement over the three perotation repetitions for Sequence A, but performance continued to improve for Sequence B. Performances in the first trials of perotation and postotation were poorer than in the trials preceding them, followed by an immediate improvement in the later trials under the same condition.

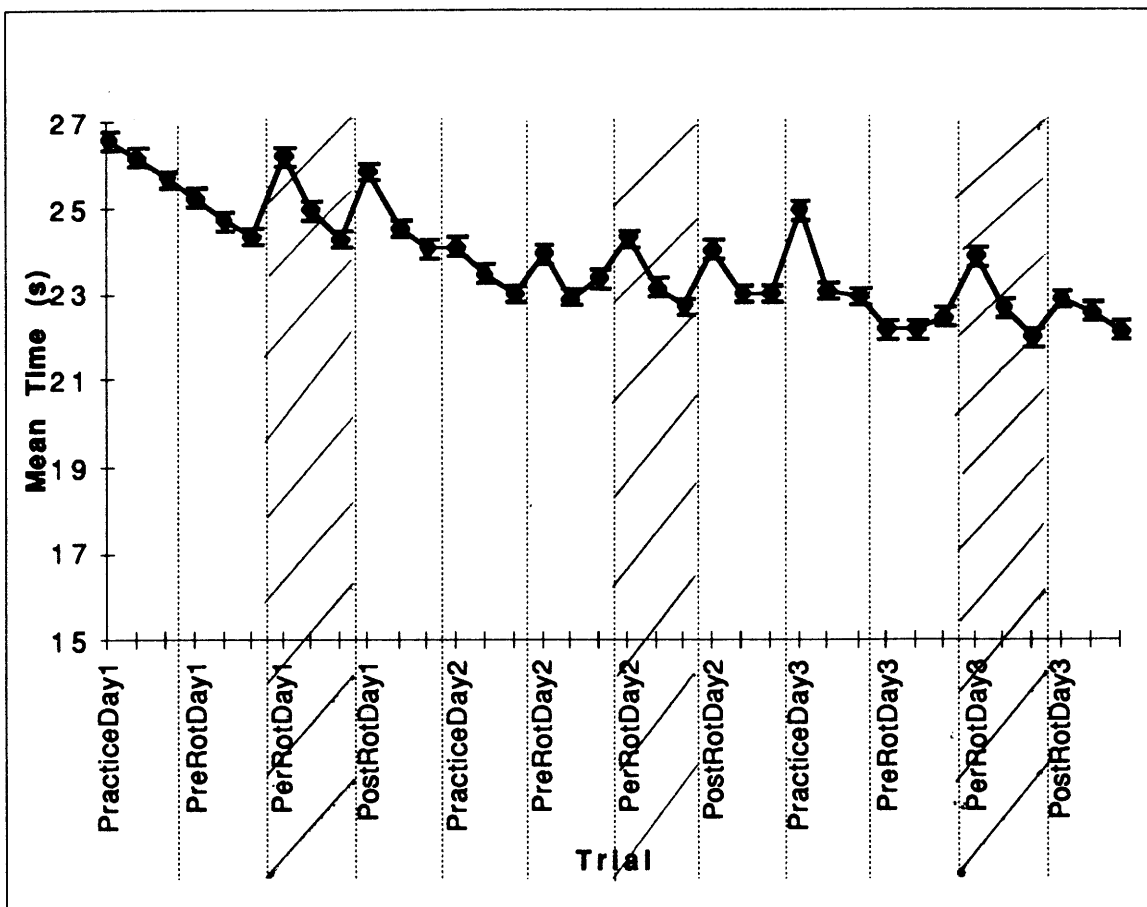


Figure 6-6 Mean Times for Sequence B Trials Averaged Over All Subjects

The subjects mastered two-handed tasks requiring eye-hand coordination even when their head motion was limited by the need to avoid stimulating their semicircular canals. This is an encouraging finding.

7.0 Recommended Future Research

This study could be replicated with both clockwise and counter clockwise rotations, balancing and contrasting the expected effects of the reversing Coriolis forces. It will be important to note what motions are being performed and what Coriolis forces may be aiding subjects. In addition, studies should be conducted where the subject's head is not at the center of rotation. The current study was limited by the desire to avoid nauseating

subjects. In a rotating space vehicle astronauts will experience greater Coriolis forces since they will be farther from the center of rotation.

Most importantly, during future research, it is suggested that tasks involving more and larger hand movements be utilized. This requires having more space for subjects to move their arms than was available with the MIT-AGS. In order to further investigate if adaptation is specific to certain tasks, several tasks should be chosen so that different tasks may be performed after subjects have adapted to the rotating environment. The performances in several tasks that involve similar arm motions should be compared to those in tasks that involve completely different motions.

8.0 References

- Bailey, R. W.: *Human Performance Engineering: Using Human Factors/Ergonomics to Achieve Computer System Usability*. Englewood, New Jersey: Prentice Hall, 1989.
- Boff, K. R. and Lincoln, J. E.: Environmental Stress, Fatigue, and Circadian Rhythms. *Engineering Data Compendium: Human Perception and Performance*, 3, 10.102, AAMRL, Wright-Patterson AFB, Ohio, 1988.
- Clark, B. and Graybiel, A.: Human Performance During Adaptation to Stress in the Pensacola Slow Rotation Room. *Aerospace Medicine*, 32: 93-106, 1961.
- Diamandis, P. H.: The Artificial Gravity Sleeper: A Deconditioning Countermeasure for Long Duration Space Habitation. Master of Science Thesis. Cambridge, Massachusetts: Massachusetts Institute of Technology, 1988.
- DiZio, P. and J. R. Lackner.: Small Changes in Gravitoinertial Force Background Affect Adaptation to Coriolis Force Perturbations of Reaching Movements. Unpublished as of October 11, 1995.
- Graybiel, A., Clark, B. and Zarriello, J. J.: Observations on Human Subjects Living in a "Slow Rotation Room" for Periods of Two Days. *Archives of Neurology*, 3: 55-73, 1960.
- Graybiel, A., Kennedy, R. S., Knoblock, E. C., Guedry, F. E., Jr., Mertz, W., McLeod, M. E., Colehour, J. K., Miller, E. F., II and Fregly, A. R.: Effects of Exposure to a Rotating Environment (10 RPM) on Four Aviators for a Period of Twelve Days. *Aerospace Medicine*, 35:733-754, 1965.
- Green, J. A. and Peacock, J. L.: Effects of Simulated Artificial Gravity on Human Performance. NASA CR-2129. Downey, California: North American Rockwell Corp. Space Division, for Langley Research Center, 1972.
- Guedry, F. E., Jr., Kennedy, R. S., Harris, C. S. and Graybiel, A.: Human Performance During Two Weeks in a Room Rotating at Three RPM. NASA Order No. R-47. Pensacola, Florida: Naval School of Aviation Medicine, 1962.
- Kennedy, R. S. and Graybiel, A.: Symptomatology During Prolonged Exposure in a Constantly Rotating Environment at a Velocity of One Revolution per Minute. *Aerospace Medicine*, 33: 817-825, 1962.
- Kennedy, R. S., Tolhurst, G. C. and Graybiel, A.: The Effects of Visual Deprivation on Adaptation to a Rotating Environment. NASA Order No. R-93 (N66-15435). Pensacola, Florida: Naval School of Aviation Medicine, 1965.
- Lackner, J. R.: Orientation and Movement in Unusual Force Environments. *Psychological Science*, 4(3): 134-142, 1993.
- Lackner, J. R. and DiZio, P.: Rapid Adaptation to Coriolis Force Perturbations of Arm Trajectory. *Journal of Neurophysiology*, 72(1): 299-313, 1994.

- Loret, B. J.: Optimization of Space Vehicle Design with Respect to Artificial Gravity. *Aerospace Medicine*, 34: 430-441, 1963.
- Peacock, J. L. and Green, J. A.: Initial Assessment of Various Human Behavior Capabilities in a Rotating Environment. Presented at the AIAA/ASMA Weightlessness and Artificial Gravity Meeting, August 9-11, 1971, Williamsburg, Virginia, AIAA Paper No. 71-888.
- Piland, W. M., Hausch, H. G., Maraman, G. V. and Green, J. A.: Design of Experimental Studies of Human Performance Under Influences of Simulated Artificial Gravity. Fifth Symposium on the Role of the Vestibular Organs in Space Exploration. NASA SP-314. Aug. 19-21,1970, Pensacola, Florida, pp. 55-65.
- Ramsey, H. R.: Human Factors and Artificial Gravity: A Review. *Human Factors*, 13(6): 533-542, 1971.
- Stone, R. W., Jr.: An Overview of Artificial Gravity. Fifth Symposium on the Role of the Vestibular Organs in Space Exploration. NASA SP-314. Aug. 19-21,1970, Pensacola, Florida, pp. 23-33.
- Stone, R. W., Jr. and Letko, W.: The Effects of Angular Motion of Rotating Space Vehicles on the Ability of an Astronaut to Perform Simple Tasks. Institute of Environmental Sciences Proceedings of 1962 Conference, April 11-13, 1962, Chicago, Illinois, pp. 481-489.
- Stone, R. W., Jr. and Letko, W.: Effects of Rotation on the Ability of Subjects to Perform Simple Tasks. In: A Report on the Research and Technological Problems of Manned Rotating Spacecraft. NASA TN D-1504. Hampton, Virginia: Langley Research Center, 1962, pp. 85-90.
- Stone, R. W., Jr. and Letko, W.: Tolerance to Vehicle Rotation of Subjects Using Turning and Nodding Motion of the Head While Performing Simple Tasks. AIAA Paper No. 64-218, 1964.

9.0 Appendices

Appendix A: COUHES

Committee on the Use of Human Subjects Approval Form & Final Consent Form

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Committee on the Use of Humans as Experimental Subjects

Application for Approval to Use Humans as Experimental Subjects

PART I.

DATE: 5/7/96

Title of Study: The Effect of Short-Arm Centrifugation on Human Performance and Physiology

Principal investigator: Professor Laurence Young

Department: Aeronautics & Astronautics

Room No.: 37-219

Telephone No.: 253-7759

Associated Investigators :	Dawn Hastreiter	253-7509
	Anna Tomassini	253-7509

Collaborating Institution(s), if applicable: none

Financial Support: NASA Grant NAGW-3958 Visual-Vestibular Interaction

Purpose of Study: The investigation is divided into two components: human performance and human physiology. Please see the following pages for discussions of the purposes of each of the components.

The Effects of Short-Arm Centrifugation on the Cardiovascular System

Purpose of Study

Exposure to microgravity causes significant physiological changes. One of the proposed mechanisms for countering these affects for long-duration missions is artificial gravity in space. Proposals include spinning the entire spacecraft or incorporating a short-arm centrifuge (SAC) into the spacecraft. Short-arm centrifugation in a non-rotating craft may ease some engineering and astrodynamics requirements. Before a SAC could be tested in space, a significant number of ground studies must be conducted to determine the effects of a gravity gradient both on a normal person and individuals undergoing treatment, such as bed rest, that produces similar physiological microgravity effects.

This study focuses on determining several of the cardiovascular effects of a gravity gradient on a normal person. Two contemporary investigations have recently been performed. Cardús (1993) performed a study on six men with measurements of general cardiovascular signals for one hour durations on a device similar to the MIT-Artificial Gravity Simulator (AGS), a short-arm centrifuge. He found that few changes were seen for G levels below 1 at the feet. Cardiovascular trends did change in the range 1-1.5 G at the feet. Above 1.5 G, cardiovascular changes became more dramatic with 2 G at the feet being near the safe physiological limit. Researchers at NASA's Ames Research Center (Breit, et al. 1996) also conducted a study on men and women to compare the effects of short-arm centrifugation, long-arm centrifugation, whole-body tilting, and lower body negative pressure on blood flow rates and baroreceptor stimulation. Their investigation was limited to G levels of 1 and below at the feet. Confirming Cardús's earlier study, few significant overall cardiovascular changes were seen below 1 G at the feet. Some baroreceptor stimulation did occur.

The purpose of this study is to extend the work of the previous researchers. Heart rate variability, heart rate, ECG signals, fluid shift to the legs, and blood pressure will be assessed in men and women for G levels at the feet up to 1.5. Determining how a gravity gradient affects the cardiovascular system will enable future researchers to more precisely outline studies necessary on individuals undergoing bed rest treatments as models for spaceflight deconditioning.

The Effect of Coriolis Forces on the Human Performance of Two-Handed Tasks While in a Rotating Environment

Purpose of Study

One of the proposed means of preventing physiological deconditioning during long-term space missions, such as traveling to Mars, is to create artificial gravity by rotating the spacecraft. However, while artificial gravity may help prevent the physiological problems induced by microgravity, the unfamiliar gravity gradients and Coriolis forces which result cause problems with motions attempted in the rotating environment (Loret, 1963; Stone, 1970; Ramsey, 1971; Lackner, 1993). Ever since the idea of rotating space vehicles evolved, studies have been conducted on the effects of artificial gravity on human performance. The studies conducted at the Pensacola Slow Rotation Room consisted of various tests to assess human performance while in a rotating environment, however, the researchers were mainly concerned with the effects on the vestibular system and the brainstem activating system (Graybiel, Clark, and Zariello, 1960; Clark and Graybiel, 1961; Kennedy and Graybiel, 1962; Graybiel et al., 1965; Guedry, 1962). In addition, the subjects were not oriented as they would be in an artificial gravity environment. Studies conducted by the North American Rockwell Corporation and Langley Research Center were in simulators where the subjects were rotated about an axis perpendicular to their body axis, as if in a rotating space vehicle (Stone and Letko, 1962(1), 1962(2), 1964; Piland et al., 1970; Green and Peacock 1972). Unfortunately, experiments involving complex two-handed tasks that would be affected by Coriolis forces were not conducted.

The purpose of this portion of the study is to investigate how the Coriolis forces created by rotation affect the subjects' ability to perform motor tasks requiring two-handed hand-eye coordination. The importance of two-handed tasks lies in the different Coriolis forces which must be compensated for when the two hands do not move with identical direction and speed. The motivation is that during long-term missions it is very important for astronauts to still be able to complete their required tasks efficiently while experiencing artificial gravity. Stone and Letko looked at how Coriolis forces affect the performance of simple perceptual motor skills, as did Lackner and DiZio (1994) with their experiments on the ability of subjects to point at targets while rotating. However, neither used complex two-handed tasks, and Lackner and DiZio performed their experiments in Brandeis University's rotating room with subjects in a different orientation to that of an artificial gravity environment.

PART II.

EXPERIMENTAL PROTOCOL

Please see the following comments for the two experimental protocols of the investigation.

Experimental Protocol for Human Physiology Study:

Experimental subjects will be chosen with the aid of the attached selection questionnaire. Volunteers with histories of heart conditions, loss of consciousness, respiratory disorders, and other medical conditions that contraindicate participation will be asked not to participate. Individuals with the above histories may be placed in physical danger during rotation on the MIT-Artificial Gravity Simulator (AGS). Susceptibility to motion sickness should not necessarily eliminate a volunteer for the physiological studies because it is not anticipated to be a major side effect.

The height, weight, and certain characteristic lengths of the subject will be measured. Subject height is necessary to determine what rotation rate will produce a certain G level at the feet. Subject weight will be used to determine if any correlation exists between weight and the results of the experiment. Distance measurements referenced from the top of the head, such as location of the vestibular system and heart, will also be obtained to calculate the force stimulation level of these body systems.

Subjects will be placed supine on the AGS, pictured in Figure 1, such that the top of their head is at the center of rotation. Since the AGS is of such short-radius, subjects experience a 100% z-axis force gradient along their body. All subjects will be rotated up to the experimentation speed with an onset rate no greater than 1 rpm/s. Rotation rate will be such that the equivalent G level in the plane of rotation at the subject's feet will not exceed 1.5 G. 1.5 G at the feet corresponds to a rotation rate of 27.1 rpm and 29.7 rpm for 5-ft. and 6-ft. individuals, respectively. Rotation will last for no more than one hour. For the actual physiological trials, rotation will be preceded by at least a ten minute stationary period with cardiovascular monitoring. Also, at least a fifteen minute monitoring period will be observed after each one hour rotation.

Three cardiovascular measuring devices will be attached to the subject during the protocol: a electrocardiograph (ECG), a blood pressure monitor, and an impedance plethysmograph. The ECG will trace the heart rhythm, which will be studied afterwards for heart rate variability and any abnormalities. ECG leads will be placed near each clavicle and on one side of the abdomen. The leads have an adhesive undersurface and an attempt will be made to place them in hairless areas. Blood pressure and heart rate will be measured every five minutes by an automatic blood pressure cuff placed on the subject's right arm. The impedance plethysmograph to be used will measure the electrical resistance in the calf. Resistance in the calf corresponds to volume in the calf. The impedance plethysmograph requires four circumferential electrodes to be placed on the subject. 4 mA of AC current at 100 kHz is passed through the outer 2 electrodes, and the resistance measurement is taken from the inner two electrodes. The Minnesota Impedance Cardiograph Model 304 B will be used for the impedance plethysmography. The device has been used for approximately 20 years for safe resistance measurements of the body. Circumferential measurements of the calf before and after trials will be used to correlate actual volume change to resistance changes. Circumference measurements will be taken at pre-administered marks on the subject's calf. All leads from the physiological monitoring equipment are attached to slip rings in the shaft of the AGS support rod and terminate at a computer system. In addition, the leads will be well insulated for the safety of the subjects.

After testing equipment on several volunteers, actual experimental trials will begin. The protocol will require at least four sessions with each subject. We anticipate one control session consisting of approximately: one hour of supine rest on the AGS, one half hour of standing, and a final half hour of supine rest on the AGS. The three experimental runs will

likely include: one half hour of supine rest on the AGS, one hour of rotation, and a final half hour of supine rest on the AGS. Three rotation rates are anticipated for each subject, resulting in 0.5, 1.0, and 1.5 G's at the feet. Additional trials at intermediate rotation rates or durations may be requested from subjects. Trials will most likely take place on different days at the subject's convenience. From the long duration physiological measurements at different G levels, investigators hope to discover the time and force dependent cardiovascular effects of a gravity gradient.

In addition to the informed consent form for AGS rotation, experimental trial subjects will receive an outline of the trials with a statement of purpose.

Experimental Protocol for Human Performance Study:

The experiment will be conducted at the MIT Man-Vehicle Laboratory on a rotating platform originally designed in a previous Master's thesis project to investigate sleeping during rotation (Diamandis, 1988). (This project received COUHES approval #1688 in June of 1986.) The platform is 3 ft wide with a radius of 7 ft and has a counterweight at one end. Subjects will be rotated at 10 rpm with their head at the center of rotation. This rotation rate matches that which would be used for a 4m radius vehicle, creating a centripetal force of about 0.5G at the rim, which is a proposed design for a Mars vehicle. The head placement at the center of rotation will help prevent motion sickness.

An experiment hood will be placed above the subjects near eye-level so that they may perform their tasks while lying on the rotating platform with minimal head movement. There are various means of measuring performance, including vigilance, serial reaction, tracking, and memory tasks; however, alertness, speed, accuracy, and short-term memory capacity are considered more reliable measures of the effect of stressors (Boff and Lincoln, 1988). Speed and accuracy will be used in this study as measures of the performance of motor tasks while under the stress of a rotating environment.

Preliminary static tests will be performed to assess the learning curve for the different tasks. Preliminary tests are required since subjects naturally improve in their performance of a certain task logarithmically each time they perform that specific task. Speed and accuracy are increased by fifty percent between the first and second time a task is done. Completion time is again improved by half the previous amount the next time that task is executed, and so on. The purpose of the initial tests is to reach an asymptotic level of performance, which should occur after three to five trials, before conducting the experiments so that the effect of Coriolis forces can be differentiated from any learning process. Two different tasks will be considered: a modified Stromberg Dexterity Test and a modified Bolt Test. The original Stromberg Dexterity Test (Peacock and Green, 1971) required erect subjects to place 54 cylindrical blocks of three different colors into correspondingly colored holes that were on a flat plane in front of them using only one hand. The modified test used in this study will involve having the cylindrical blocks dispersed to the right, left, and in front of the subject while he switches the order of the blocks using both hands. The performance of this task will be measured by time to completion of the test run. The other task being considered, the Bolt Test (Kennedy, Tolhurst and Graybiel, 1965), involves placing three washers onto a bolt and placing the bolt into a hole. Here the washers and bolts will be picked up from different locations to the left and to the right of the subject, and the finished product will be placed into a hole in front of the subject. Performance for the Bolt Test will also be measured in time to completion of the test run, which involves 30 bolts. Two test runs will be performed for each session of the chosen task. The exact task which will ultimately be performed will be determined during the preliminary learning curve study according to the reliability associated with each task.

The actual experimentation will involve a training session before rotation and test sessions during and after rotation for the task chosen during the preliminary study. Subjects will be loosely strapped onto the platform and a communication check will be made of the headsets prior to spin up. The platform will be gradually accelerated to a constant velocity of

10 rpm over a period of about 30 seconds. Two minutes will elapse before starting the tests in order to allow the subject to get accustomed to the accelerated environment. After completing two runs of the selected task, the platform will be gradually spun down to 0 rpm. Two minutes will again elapse before post-rotation tests begin, which will be an exact repetition of the test runs performed before and during rotation. In addition, to look at adaptation to the artificial gravity environment, the subjects will be asked to do another set of pre-, per-, and post-rotation test sessions about three days following the initial testing and again five days after the second test session. Subjects will have the ability to stop rotation by pressing a button if so desired at any time, and they will be constantly monitored through a video monitor and audio communication. If the subject should try to sit up during rotation, the two quick-release safety belts would open the same circuit as the subject's emergency button and stop the platform. The emergency cessation of rotation will occur gradually, but at a faster rate than normal spin up or spin down so as to reach 0 rpm in 5 seconds.

PART III. Please answer each question below, and indicate "NA" where not applicable to your application. Positive answers should be briefly explained, with detailed information included in PART II.

1. How will subjects be obtained?
Subjects will be volunteers recruited from the MIT community.

Number of subjects needed? Preferably, at least 10.

Age(s) of subjects?
Subjects must be at least 18. Participation will be limited to subjects under the age of forty except for the Principal Investigator and trained astronauts.
2. Will women and minorities be recruited? Yes.
If not, explain why.
3. Will subjects receive any payment or other compensation for participation?

Subjects who are not members of the Man Vehicle Laboratory will receive compensation.
4. Will your subjects be studied outside MIT premises? No.
If so, please indicate location.
5. Will the facilities of the Clinical Research Center be used? No.
If so, the approval of the CRC Advisory Committee is also required.
6. Will drugs be used? No.
Any Investigational New Drugs (IND)? No.
7. Will radiation or radioactive materials be employed? No.
If so, your study must also be approved by the Committee on Radiation Exposure to Human Subjects. Application forms are available from Mr. Francis X. Masse, Radiation Protection Office, 20C-207, x3-2180.
8. Will special diets be used? If so, please state proposed duration(s).

Subjects in the physiological studies will be asked to refrain from alcohol and caffeine intake for 24 hours prior to each experimentation period.

9. Will subjects experience physical pain or stress?

Subjects may possibly feel slight, non painful pressure in their legs due to fluid shift caused by centrifugation. Some subjects may experience a headache due to fluid shift. While they will be instructed not to move their head, motion sickness may result if the subjects do not comply. Claustrophobia may be experienced by some subjects in the human performance study. Subjects can end rotation gradually and safely at any point with an emergency stop switch near their hand position.

10. Will a questionnaire be used? Yes. (Copy is attached.)

11. Are personal interviews involved? No.
If so, include an explanation in Part II and attach an outline.

12. Will subjects experience psychological stress? No.

13. Does this study involve planned deception of subjects? No.

14. Can information acquired through this investigation adversely affect a subject's relationships with other individuals (e.g. employee-supervisor, patient-physician, student-teacher, co-worker, family relationships)? No.

15. Please explain how subject's anonymity will be protected, and/or confidentiality of data will be preserved.

Subjects will be coded. Only the code number will appear in any dissemination of data.

PART IV.

A. *Please summarize the risks to the individual subject and the benefits, if any;*

include any possible risk of invasion of privacy, embarrassment or exposure of sensitive or confidential data, and explain how you propose to deal with these risks.

1. Headaches, Pressure in the Legs

These possible effects are caused by a fluid shift in the body due to centrifugation. On initial report of a headache from a subject, an investigator will suggest relaxation techniques to relieve the headache. If the headache persists for the longer than 5 minutes, the experiment will stop. The subject also has the option of ending the experiment at any time for any reason. In previous studies of this nature, no subject elimination was reported based on these effects.

2. Nausea/Motion Sickness

Motion sickness is primarily due to sensory conflict. The subject tactually perceives himself as lying on a still bed after an initial period on the bed. Movements of the head and the resulting vestibular stimulation reveal the influence

of Coriolis forces due to rotation. The canopy of the AGS is translucent and the subject sees a blurring of external objects during rotation. The consequent sensory conflict may cause nausea. For the physiological studies on the AGS, the subjects will be blindfolded and instructed not to move their head. In both experiments subjects will be told that moving their head may make them nauseous. In addition, the canopy will be covered with an opaque material for the performance studies and subjects will be asked to focus of the experiment hood (which is stationary with respect to them) and their tasks. If the subject reports intolerable motion sickness, the experiment will be stopped. The subject also has the option of ending the experiment at any time for any reason with an emergency switch.

3. Claustrophobia

Subjects in the human performance study may experience claustrophobia due to the placement of the experiment hood. Volunteers with known claustrophobia will be asked to decline participation. The subject has the option to end the experiment at any time.

4. Heart Rate Increase

Previous research has shown that rotation with G levels at the feet between 1 and 1.5 G causes increased heart rate of up to 1.75 times normal supine levels. While the increased heart rate is no greater than that which would be experienced during aerobic exercise, medical heart conditions unknown to the subject may become evident. The heart rate of the subjects in the physiological studies will be continuously monitored. If heart rate becomes abnormally high, 1.75 times the subject's normal heart rate, the experiment will be stopped. Maximum heart rate for an individual is $HR(\max) = 220 - \text{age}$. Subjects will also be monitored for complications for at least 15 minutes after each rotation session in the physiological studies.

5. Injury Related to Falling Off the AGS While Rotating

Serious injury could result from falling off the AGS while it is rotating. The following steps will be taken to prevent such an incident:

- a. The subject will be loosely restrained at the legs and thorax, preventing him from making sudden motions or falling off the rotating bed. The restraints will be equipped with quick release latches making it possible for the subject to escape quickly if necessary.
- b. Side railings similar to those on a hospital stretcher will be employed to contain the subject.
- c. As mentioned previously, the subject will be equipped with an emergency stop switch which will stop the AGS from rotating within approximately 5 seconds.
- d. The subject will be continuously monitored by at least one experimenter in the same room.
- e. The subject will be equipped with a 2-way headset communication system connected to the observing experimenter.
- f. Final human performance measurements will employ a video camera mounted on the AGS which may help the investigator understand the nature of any problems that arise.
- g. Finally, subjects will experience a short test ride of several minutes duration after familiarization with the equipment.

6. Skin Irritation

Subjects in the human physiology study will have seven electrodes placed on their bodies. Sufficient electrical contact with the skin requires that electrode gel be placed between the leads and skin. Also, calf volume measurements require

marking the leg with a washable marker to ensure consistency of measurements. The application of gel and marker to the skin may cause minor skin irritation. However, the irritation is unlikely to be lasting.

- B .** *Detection and reporting of harmful effects:* If applicable, please describe what follow-up efforts will be made to detect harm to subjects, and how this committee will be kept informed.

All AGS studies involve multiple sessions on different days. Detection of harmful effects during exposure will occur by asking the subjects how they feel after every 15 minutes of rotation and if they wish to continue. Subjects will also have the opportunity to report any harmful effects noticed since the last exposure before commencing the next trial. In addition, all physiological studies involve a 15-30 minute monitoring period after each trial, and the human performance studies involve post-rotation tests. In the event of harmful effects, COUHES will be informed verbally or through written communication, depending on the severity of the situation.

PART V.

INFORMED CONSENT MECHANISMS:

Please send the following attachment.

The committee is mandated by the DHHS and Institute regulations to require documented informed consent. The document should be retained as a permanent record. Under certain circumstances, the committee may waive documentation. The elements of such informed consent are:

1. Consent forms should start with a statement that participation is voluntary and that the subject is free to withdraw his/her consent and to discontinue participation in the project or activity at any time without prejudice to the subject.
2. A fair explanation of the procedures to be followed and their purposes, including identification of any procedures which are experimental.
3. A description of any attendant discomforts and risks reasonably to be expected.
4. A description of any benefits to the subject that are reasonably to be expected.
5. A disclosure of any appropriate alternative procedures that might be advantageous for the subject.
6. An offer on the part of the investigator to answer any inquiries concerning the procedures.
7. There shall be no exculpatory language making the subject waive or seem to waive any rights.
8. In addition, the following statement or a comparable one (in the case of cooperating institutions) shall appear on all informed consent documents, except

that in certain cases in non-biomedical disciplines, COUHES may decide that it may be omitted:

"In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights.*

"I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, MIT 253-6787, if I feel I have been treated unfairly as a subject."

Consent forms used in cooperating institutions must assure that the rights of the subject are protected at least to the same degree.

*Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.

These elements should be clearly stated in a document to be signed by the subject or a legally authorized representative in the case of minors or incompetent individuals. The material presented in such a document must be in clear English, easily understandable to the least educated of subjects. Where minors are involved as subjects, due consideration should be given to their capability to give consent. The informed consent document should be signed by both the subject and parent or guardian wherever possible.

In the case of Questionnaires or Interviews, the Committee may decide that a consent form is not required if the intent is merely to obtain the requested information. However, it must be made clear to the subject that:

- Participation is voluntary.
- The subject may decline to answer any questions.
- The subject may decline further participation at any time without prejudice.
- Confidentiality and/or anonymity are assured.

In addition:

- No coercion to participate will be involved. For example, handing out or collecting questionnaires personally may be so interpreted.
- The data collected will be reported in such a way that the identity of individuals is protected.
- Proper measures will be taken to safeguard the data.

Other examples of situations in which informed consent documentation is not required include use of discarded blood, certain psychological studies involving intentional deception, or record searches and use of stored data. In a case of any deception, debriefing

mechanisms must be acceptable before approval of an application may be complete. The Committee expects the investigators will notify the Committee if any adverse side effects occur.

Signature of Principal Investigator _____ Date _____

Print Full Name: Laurence Young

Signature of Department Head _____ Date _____

Print Full Name: Earll Murman

Please return this application with 3 photocopies to:
H. Walter Jones, Jr. M.D.
COUHES Chairman
E23-389
253-6787

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MAN-VEHICLE LABORATORY

THE EFFECTS OF SHORT-ARM CENTRIFUGATION
ON THE CARDIOVASCULAR SYSTEM

CONSENT FORM

I have been asked to participate in a study of the effects of short-arm centrifugation on the cardiovascular system. I understand that participation is voluntary and that I may withdraw consent and discontinue participation at any time for any reason. I have completed a selection questionnaire related to my medical history and understand that I should not participate in this study if I have any medical heart or respiratory conditions, if I have any medical conditions which would be triggered if I develop motion sickness, or if there is any possibility that I may be pregnant. I understand that participation in the investigation under any of the above circumstances may put me in danger. I agree to abstain from caffeine and alcohol intake 24 hours prior to each experimentation period since this may affect cardiovascular measurements. My participation as a subject on the AGS involves either testing of equipment or actual experimental trials.

Prior to rotation, I will be oriented to the MIT-Artificial Gravity Simulator (AGS) and all cardiovascular monitoring equipment. I understand that my height, weight, and certain characteristic lengths, such as location of my heart, may be measured. During rotation I may have several medical devices or leads attached to my body. These would consist of a blood pressure monitor, ECG leads, and/or an impedance plethysmograph around one of my calves. A description of how these devices will feel has been presented to me. I agree to participate in possible stationary monitoring periods before or after rotation.

Rotation on the AGS will not exceed the following parameters:

- onset rate no greater than 1 rpm/s
- G level at my feet no greater than 1.5 G
- time of rotation will not exceed 1 hour.

I understand that these are well within the safe limits for short-radius rotation. I can end rotation at my discretion by pressing the subject's stop button, the use of which has been demonstrated to me.

I understand the following risks and the listed steps investigators have taken to minimize those risks.

1. Headaches, Pressure in the Legs

These possible effects are caused by a fluid shift in the body due to centrifugation. On initial report of a headache from a subject, an investigator will suggest relaxation techniques to relieve the headache. If the headache persists for the longer than 5 minutes, the experiment will stop. The subject also has the option of ending the experiment at any time for any reason.

2. Nausea/Motion Sickness

Motion sickness is primarily due to sensory conflict. The subject tactually perceives himself as lying on a still bed after an initial period on the bed. Movements of the head and the resulting vestibular stimulation reveal the influence of Coriolis forces due to rotation. The canopy of the AGS is translucent and the subject sees a blurring of external objects during rotation. The consequent sensory conflict may cause nausea. For the physiological

studies on the AGS, the subjects will be blindfolded and instructed not to move their head. If the subject reports intolerable motion sickness, the experiment will be stopped. The subject also has the option ending the experiment at any time for any reason with an emergency switch.

3. Heart Rate Increase

Previous research has shown that rotation with G levels at the feet between 1 and 1.5 G causes increased heart rate of up to 1.75 times normal levels. While the increased heart rate is no greater than that which would be experienced during aerobic exercise, medical heart conditions unknown to the subject may become evident. The heart rate of the subjects in the physiological studies will be continuously monitored. If heart rate becomes abnormally high, 1.75 times the subject's normal heart rate, the experiment will be stopped. Maximum heart rate for an individual is $HR(\text{max}) = 220 - \text{age}$. Subjects will also be monitored for complications for at least 15 minutes after each rotation session in the physiological studies.

4. Injury Related to Falling Off the AGS While Rotating

Serious injury could result from falling off the AGS while it is rotating. The following steps will be taken to prevent such an incident:

- a. The subject will be loosely restrained at the legs and thorax, preventing him from making sudden motions or falling off the rotating bed. The restraints will be equipped with quick release latches making it possible for the subject to escape quickly if necessary.
- b. Side railing similar to those on a hospital stretcher will be employed to contain the subject.
- c. As mentioned previously, the subject will be equipped with an emergency stop switch which will stop the AGS from rotating within approximately 5 seconds.
- d. The subject will be continuously monitored by at least one experimenter in the same room.
- e. The subject will be equipped with a 2-way headset communication system connected to the observing experimenter.
- f. Final human performance measurements will employ a video camera mounted on the AGS which may help the investigator understand the nature of any problems that arise.
- g. Finally, subjects will experience a short test ride of several minutes duration after familiarization with the equipment.

5. Skin Irritation

Subjects will have seven electrodes place on their bodies. Sufficient electrical contact with the skin requires that electrode gel be placed between the leads and skin. Also, calf volume measurements require marking the leg with a washable marker to ensure consistency of measurements. The application of gel and marker to the skin may cause minor skin irritation. However, the irritation is unlikely to be lasting.

If I am a participant in experimental trials, I tentatively agree to return for additional trails (at most 10) requested by the experimenter. However, I understand that I can withdraw from this study at any time for any reason. I understand that the likely protocol for the actual trials will consist of the following four sessions, the order of which will be determined by the experimenter:

1. control session: one hour of supine rest on the AGS, one half hour of standing, and a final half hour of supine rest on the AGS
2. one half hour of supine rest on the AGS, one hour of rotation resulting in 0.5 G's at my feet, and a final half hour of supine rest on the AGS
3. one half hour of supine rest on the AGS, one hour of rotation resulting in 1.0 G's at my feet, and a final half hour of supine rest on the AGS

4. one half hour of supine rest on the AGS, one hour of rotation resulting in 1.5 G's at my feet, and a final half hour of supine rest on the AGS.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights. (Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.)

Monetary compensation for those who are not members of the Man-Vehicle Laboratory will be \$10 per hour.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, H. Walter Jones, Jr. M.D. (MIT E23-389, 253-6787), if I feel I have been treated unfairly as a subject.

I have been informed as to the nature and purpose of this experiment and the risks involved, and agree to participate in the experiment. I understand that participation in this experiment is voluntary, and I am free to withdraw my consent and to discontinue participation in the study at any time without prejudice.

Subject _____
Subject Code No.: _____

Date _____

Experimenter _____

Date _____

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
MAN-VEHICLE LABORATORY

THE EFFECT OF CORIOLIS FORCES ON THE HUMAN PERFORMANCE OF TWO-
HANDED TASKS WHILE IN A ROTATING ENVIRONMENT

CONSENT FORM

I have been asked to participate in a study of the effects of the forces produced by rotation on the performance of two-handed tasks. I understand that participation is voluntary and that I may withdraw consent and discontinue participation at any time for any reason. I have completed a selection questionnaire related to my medical history and understand that I should not participate in this study if I have any medical heart conditions, if I have any medical conditions which would be triggered if I develop motion sickness, or if there is any possibility that I could be pregnant.

Prior to rotation, I will undergo a static training session while lying on the platform in which I will be taught and have the chance to practice the manual task which I will be asked to perform while rotating. The manual task involves simultaneous use of both my hands. After I have learned the task, a prerotation test session will be conducted. During the next portion of the experiment I will be rotated at a speed of 10 RPM, a speed well within the established safety limits, while still lying on my back. During the first few minutes of rotation while the platform comes up to speed, I will probably feel some slight dizziness. If I do become dizzy I will close my eyes and relax until the sensation goes away. After the initial start-up phase, my balance system will adapt to the constant rotational rate, and sensation of spinning should be greatly reduced. At this point I will be asked to perform the manual tasks learned in the training session. During this portion of the experiment I may experience nausea or disorientation, especially if I move my head. To reduce the possibility of nausea, a padded headrest will be provided to help reduce the amount of head movement, and all objects I will have to interact with will be in my immediate line of sight.

I will be prevented from falling off the platform by two side rails and two quick-release safety belts, one at chest level and one at my legs. I should not try to sit up or make fast head movements while rotating; if I try to sit up the safety belt at my chest will be released and will stop the rotation of the platform. My hands will be free to move within the confines of the hand rails and wind canopy. In the case of an emergency, or if I have an immediate desire to stop rotation, there will be an easily accessible stop switch (the use of which has been demonstrated to me) within arms reach which will bring the platform to a halt within approximately 5 seconds. I will be in constant communication with the experimenter through headsets and will be monitored by a video camera. If I experience unacceptable symptoms, I am free to close my eyes, ask for a break, or withdraw entirely from the experiment at any time. I understand that rotation sessions will not exceed thirty minutes and that I may be asked to come back two more times in order to investigate adaptation to artificial gravity, once three days after the initial test session, and again five days after the second test session.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not

waiving any of my legal rights. (Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.)

Monetary compensation for those who are not members of the Man Vehicle Laboratory will be \$10 per hour.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, H. Walter Jones, Jr. M.D.(MIT E23-389, 253-6787), if I feel I have been treated unfairly as a subject.

I have been informed as to the nature and purpose of this experiment and the risks involved, and agree to participate in the experiment.

I understand that participation in this experiment is voluntary, and I am free to withdraw my consent and to discontinue participation in the study at any time without prejudice.

Subject _____ Date _____

Experimenter _____ Date _____

References

1. Boff, K. R. and Lincoln, J. E.: Environmental Stress, Fatigue, and Circadian Rhythms. *Engineering Data Compendium: Human Perception and Performance*, 3, 10.102, AAMRL, Wright-Patterson AFB, Ohio, 1988.
2. Breit, Gregory A., Donald E. Watenpaugh, Theresa M. Buckley, Richard E. Ballard, Gita Murthy, and Alan R. Hargens. Cardiovascular responses to whole-body tilting, Gz centrifugation, and LBNP in men and women. 1996. To be published.
3. Cardús, David, and Wesley G. McTaggart. Observations on the Cardiovascular Response to the Artificial Gravity Simulator. *The Physiologist*. 1993.
4. Clark, B. and Graybiel, A.: Human Performance During Adaptation to Stress in the Pensacola Slow Rotation Room. *Aerospace Medicine*, 32: 93-106, 1961.
5. Diamandis, P. H.: The Artificial Gravity Sleeper: A Deconditioning Countermeasure for Long Duration Space Habitation. Master of Science Thesis. Cambridge, Massachusetts: Massachusetts Institute of Technology, 1988.
6. Graybiel, A., Clark, B. and Zariello, J. J.: Observations on Human Subjects Living in a "Slow Rotation Room" for Periods of Two Days. *Archives of Neurology*, 3: 55-73, 1960.
7. Graybiel, A., Kennedy, R. S., Knoblock, E. C., Guedry, F. E., Jr., Mertz, W., McLeod, M. E., Colehour, J. K., Miller, E. F., II and Fregly, A. R.: Effects of Exposure to a Rotating Environment (10 RPM) on Four Aviators for a Period of Twelve Days. *Aerospace Medicine*, 35:733-754, 1965.
8. Green, J. A. and Peacock, J. L.: Effects of Simulated Artificial Gravity on Human Performance. NASA CR-2129. Downey, California: North American Rockwell Corp. Space Division, for Langley Research Center, 1972.
9. Guedry, F. E., Jr., Kennedy, R. S., Harris, C. S. and Graybiel, A.: Human Performance During Two Weeks in a Room Rotating at Three RPM. NASA Order No. R-47. Pensacola, Florida: Naval School of Aviation Medicine, 1962.
10. Kennedy, R. S. and Graybiel, A.: Symptomatology During Prolonged Exposure in a Constantly Rotating Environment at a Velocity of One Revolution per Minute. *Aerospace Medicine*, 33: 817-825, 1962.
11. Kennedy, R. S., Tolhurst, G. C. and Graybiel, A.: The Effects of Visual Deprivation on Adatation to a Rotating Environment. NASA Order No. R-93 (N66-15435). Pensacola, Florida: Naval School of Aviation Medicine, 1965.
12. Lackner, J. R.: Orientation and Movement in Unusual Force Environments. *Psychological Science*, 4(3): 134-142, 1993.
13. Lackner, J. R. and DiZio, P.: Rapid Adaptation to Coriolis Force Perturbations of Arm Trajectory. *Journal of Neurophysiology*, 72(1): 299-313, 1994.
14. Loret, B. J.: Optimization of Space Vehicle Design with Respect to Artificial Gravity. *Aerospace Medicine*, 34: 430-441, 1963.

15. Peacock, J. L. and Green, J. A.: Initial Assessment of Various Human Behavior Capabilities in a Rotating Environment. Presented at the AIAA/ASMA Weightlessness and Artificial Gravity Meeting, August 9-11, 1971, Williamsburg, Virginia, AIAA Paper No. 71-888.
16. Piland, W. M., Hausch, H. G., Maraman, G. V. and Green, J. A.: Design of Experimental Studies of Human Performance Under Influences of Simulated Artificial Gravity. Fifth Symposium on the Role of the Vestibular Organs in Space Exploration. NASA SP-314. Aug. 19-21, 1970, Pensacola, Florida, pp. 55-65.
17. Ramsey, H. R.: Human Factors and Artificial Gravity: A Review. *Human Factors*, 13(6): 533-542, 1971.
18. Stone, R. W., Jr.: An Overview of Artificial Gravity. Fifth Symposium on the Role of the Vestibular Organs in Space Exploration. NASA SP-314. Aug. 19-21, 1970, Pensacola, Florida, pp. 23-33.
19. Stone, R. W., Jr. and Letko, W.: The Effects of Angular Motion of Rotating Space Vehicles on the Ability of an Astronaut to Perform Simple Tasks. Institute of Environmental Sciences Proceedings of 1962 Conference, April 11-13, 1962, Chicago, Illinois, pp. 481-489.
20. Stone, R. W., Jr. and Letko, W.: Effects of Rotation on the Ability of Subjects to Perform Simple Tasks. In: A Report on the Research and Technological Problems of Manned Rotating Spacecraft. NASA TN D-1504. Hampton, Virginia: Langley Research Center, 1962, pp. 85-90.
21. Stone, R. W., Jr. and Letko, W.: Tolerance to Vehicle Rotation of Subjects Using Turning and Nodding Motion of the Head While Performing Simple Tasks. AIAA Paper No. 64-218, 1964.

Updated Consent Form

MASSACHUSETTS INSTITUTE OF TECHNOLOGY MAN-VEHICLE LABORATORY

THE EFFECT OF CORIOLIS FORCES ON THE HUMAN PERFORMANCE OF TWO-HANDED TASKS WHILE IN A ROTATING ENVIRONMENT

CONSENT FORM

I have been asked to participate in a study of the effects of the forces produced by rotation on the performance of two-handed tasks. I understand that participation is voluntary and that I may withdraw consent and discontinue participation at any time for any reason. I have completed a selection questionnaire related to my medical history and understand that I should not participate in this study if I have any medical heart conditions, if I have any medical conditions which would be triggered if I develop motion sickness, or if there is any possibility that I could be pregnant. I understand that my height and weight will be measured prior to boarding the MIT Artificial Gravity Simulator (AGS). My participation as a subject on the AGS involves either testing of equipment or actual experimental trials.

Prior to rotation, I will undergo a static training session while lying on the platform in which I will be taught and have the chance to practice the manual task which I will be asked to perform while rotating. The manual task involves simultaneous use of both my hands and should be done as quickly, but as precisely, as possible. After I have learned the task, a prerotation test session will be conducted. During the next portion of the experiment, I will be rotated at a speed of 20 RPM, a speed well within the established safety limits, while still lying on my back. During the first few minutes of rotation while the platform comes up to speed, I will probably feel some slight dizziness. If I do become dizzy I will close my eyes and relax until the sensation goes away. After the initial start-up phase, my balance system will adapt to the constant rotational rate, and sensation of spinning should be greatly reduced. At this point, I will be asked to perform the manual tasks learned in the training session. During this portion of the experiment, I may experience nausea or disorientation, especially if I move my head. To reduce the possibility of nausea, a pillow will be provided to help reduce the amount of head movement, all objects I will have to interact with should be in my immediate line of sight, and a white sheet has been placed over the wind canopy to block the view of objects moving in the periphery while still letting in light.

I will be prevented from falling off the platform by two side rails and a quick-release safety belt at chest level. If the safety belt is not fastened, the AGS will not be able to start. My hands will be free to move within the confines of the hand rails and wind canopy. I should not try to sit up or make fast head movements while rotating. In the case of an emergency, or if I have an immediate desire to stop rotation, there will be an easily accessible stop button (the use of which has been demonstrated to me) within arms reach which will bring the platform to a halt within approximately 10 seconds. I will be in constant communication with the experimenter through headsets and will be monitored by a video camera. If I experience unacceptable symptoms, I am free to close my eyes, ask for a break, or withdraw entirely from the experiment at any time. I understand that rotation sessions will not exceed thirty minutes and that I may be asked to come back two more times in order to investigate adaptation to artificial gravity, once three days after the initial test session, and again five days after the second test session.

In the unlikely event of physical injury resulting from participation in this research, I understand that medical treatment will be available from the MIT Medical Department, including first aid emergency treatment and follow-up care as needed, and that my insurance carrier may be billed for the cost of such treatment. However, no compensation can be provided for medical care apart from the foregoing. I further understand that making such medical treatment available, or providing it, does not imply that such injury is the investigator's fault. I also understand that by my participation in this study I am not waiving any of my legal rights. (Further information may be obtained by calling the Institute's Insurance and Legal Affairs Office at 253-2822.)

Monetary compensation for those who are not members of the Man Vehicle Laboratory will be \$10 per hour.

I understand that I may also contact the Chairman of the Committee on the Use of Humans as Experimental Subjects, H. Walter Jones, Jr. M.D.(MIT E23-389, 253-6787), if I feel I have been treated unfairly as a subject.

I have been informed as to the nature and purpose of this experiment and the risks involved, and agree to participate in the experiment.

I understand that participation in this experiment is voluntary, and I am free to withdraw my consent and to discontinue participation in the study at any time without prejudice.

Subject _____ Date _____

Print Name _____

Subject Code No.: _____

Experimenter _____ Date _____

Appendix B: Selection Questionnaire

Artificial Gravity Study

Man-Vehicle Laboratory

SELECTION QUESTIONNAIRE

BIOGRAPHICAL INFORMATION:

Name: _____ Age: _____ Sex: _____

Address: _____ Telephone: _____

_____ Occupation: _____

PLEASE ANSWER ALL QUESTIONS TO THE BEST OF YOUR ABILITY:

1. Do you have a history of medical heart conditions (arrhythmia, heart attack, failure)? _____
2. Do you have a heart murmur that requires notification of dentist during a dental exam? _____
3. Do you have a history of seizures or epilepsy? _____
4. Do you have a history of black outs? _____
5. Do you have any breathing difficulties (asthma, bronchitis, emphysema)? _____
6. Is there any possibility you could be pregnant? _____
5. Do you have a history of claustrophobia? _____
Do you get claustrophobic: Very easily Sometimes Almost never
6. Do you have any medical conditions which might be triggered if you develop motion sickness? _____ If yes, explain: _____
7. Have you ever had motion sickness? _____ If yes, about how many times? _____
From which of the following: Car Plane Boat Game ride Other _____
Do you become motion sick: Very easily Sometimes Almost never
Approximately when did you last have motion sickness (Month/Year)? _____
8. Do you have any other chronic or acute medical problems which might place you in danger during this experiment? _____ If yes, explain: _____
9. Have you had extensive experience spinning (ice skating, dancing, game ride)? _____
Did you: Like it Dislike it Feel indifferent
10. Do you have any conditions which would prevent you from having full use of both of your arms and hands? _____

SUBJECT'S ASSIGNED CODE: _____

Appendix C: Protocol for Running MIT-AGS

PROTOCOL/SAFETY CHECK FOR RUNNING MIT ARTIFICIAL GRAVITY SIMULATOR (MIT-AGS)

- 1) Make sure no loose objects are on the MIT-AGS.
- 2) Weigh and measure height of subject.
- 3) Adjust foot plate to subject's height, making sure it is tightly fastened.
- 4) While one person puts on enough weights to counterbalance the subject, another person must hold down the opposite end of the MIT-AGS.
- 5) Using a chair placed near the center of the MIT-AGS, the subject may now climb aboard.
- 6) Use level to make sure the MIT-AGS is balanced.
- 7) Fasten safety belt around the subject's chest, making sure their arms are free to move.
- 8) Both the subject and MIT-AGS operator must put on a headset. (Prior to rotating the MIT-AGS, put the headsets to voice activation and do a communications check)
- 9) Holding the metal bars which extend down, two people should place the wind canopy on the MIT-AGS, taking care not to tear the plastic. The two metal bars near the head should be bolted into place.
- 10) Connect the ground lead of the camera to the battery, and turn the power on.
- 11) Turn the video monitor and VCR on and check that camera is in place and focused.
- 12) Extend the white sheet to the wind canopy, over the camera, and clip in place.
- 13) Clip down the wind shield at the feet.
- 14) Remove the chair used by the subject to climb on, and check for any other objects in the path of the MIT-AGS.
- 15) Extend the safety rope to the hook on the sled.
- 16) Make sure the relay for the emergency circuit is plugged in (MIT-AGS cannot be started without it)
- 17) Turn on the power to the motor controller.
- 18) Put the Stop/Start switch in the Start position.
- 19) Using the potentiometer dial, gradually increase the rotation rate of the MIT-AGS to the desired speed. (Check speed with tachometer)
- 20) Make sure subject is feeling fine. (Let subject adjust to environment before being asked to do anything else.)

- 21) When ready to stop, gradually decrease the speed of the MIT-AGS using the potentiometer.
- 22) Turn the power to the controller off.
- 23) Make sure subject does not feel too nauseous. (Let subject recover from head rush before doing anything else.)
- 24) The headsets can now be turned off and the subject may unfasten the seat belt.
- 25) Take away the safety rope.
- 26) Unclip all the wind shields.
- 27) Loosen wind canopy and remove.
- 28) Place a chair near the center of the MIT-AGS.
- 29) While one person holds down the foot-end of the MIT-AGS, the subject may climb off.
- 30) While one person continues holding down the foot-end of the MIT-AGS, another person must remove the weights which were added to counterbalance the subject.
- 31) Use the level to make sure the MIT-AGS is balanced.

Appendix D: Instructions for Subjects

INSTRUCTIONS TO BE READ TO SUBJECTS

Training

Today you will be training to perform the tasks which will be performed on the following days. You will not be rotated until tomorrow, when you will perform some practice runs prior to undergoing the baseline, rotation, and post-rotation sessions.

During this experiment you will be exchanging the position of wooden blocks, using both hands. Go as fast as you can without dropping too many blocks or putting them in the wrong place. Two sequences of block exchanges will be used: {Pointing along the patterns} 1) Switch the left and right mirror imaged blocks, going down the columns, starting from the two side panels and continuing all the way up until your hands meet at the middle of the top board. {Demonstrate} A good strategy is switching which hands the blocks are in, rather than crossing your arms, especially on the lower blocks. 2) Switch the top and bottom rows, starting from the bottom of the right board and progressing up to the top board and down the left. Do not move your head when performing the sequences because when you are rotating, sudden head movements may make you nauseous. You need to practice the sequences without moving your head. If blocks are dropped or get knocked down, just keep on going and recover them after you have finished that sequence. Pretend they are still there if you need to exchange a fallen block with another block. A box to your right contains extra blocks (some blocks may lose their washer or may fall where you can't find them). Again, do not worry about recovering the blocks until the end of a sequence. You will be given short rest periods of 1 minute or 30 seconds after each sequence to allow your arms to rest so they will not be fatigued by the end of the session.

I am giving you a headset which I will tell you to turn on prior to rotation by putting the power switch to voice activation "VOX". However, to save batteries, you shouldn't need to turn it on until that time unless you have difficulty hearing me. In addition, this white sheet will be draped over the wind canopy so that the lights are not as noticeable and do not bother you while performing the rotating session. Do you have any questions?

Day 1 of Rotation

You will be starting off with a practice session in which you will be performing the same tasks as you did yesterday in the training session. After practicing, you will perform a baseline set of sequences, followed by a set of sequences while rotating at 20 rpm, and then again after the rotation has stopped. You will be allowed to get used to the rotating environment prior to performing the tasks. In addition, you will feel a small head rush when rotation is stopped, so you will be given a rest period to recover from the headrush prior to conducting the next set of sequences.

The object is still to go as fast as you can without dropping too many blocks or putting them in the wrong place. Remember not to move your head because sudden head movements may make you nauseous while rotating. Also, if blocks fall, just keep on going and pretend they are there if you need to exchange the fallen block with another block. If blocks fall while rotating and you cannot recover them without moving your head, just leave them where they are and get a replacement from the box at your right. You will be given short rest periods of 1 minute or 30 seconds after each sequence to allow your arms to rest so they will not be too fatigued by the end of the sessions.

You will put the power switch of your headset to voice activation "VOX" when I tell you to do so. However, you don't need to turn it on until that time unless you have difficulty hearing me. You have a red emergency stop button next to you which will rapidly stop the AGS. You are not supposed to use the button in the case of nausea, because it will make you feel worse by stopping quickly. Tell me if you feel nauseous and

want to relax before continuing or want to stop the experiment. Use the button only in the case of an emergency. Do you remember the two sequences you will be performing? Do you have any questions?

Day 2 of Rotation

You will be performing the same practice, baseline, rotation, and postrotation sequences as you did 3 days ago. The object is still to go as fast as you can without dropping too many blocks or putting them in the wrong place. Remember to not move your head. If blocks fall, just keep on going and pretend they are there if you need to exchange the fallen block with another block. If blocks fall while rotating and you cannot recover them without moving your head, just leave them where they are and get a replacement from the box to your right. You will be given short rest periods of 1 minute or 30 seconds after each sequence to allow your arms to rest so they will not be fatigued by the end of the sessions.

You will put the power switch of your headset to voice activation "VOX" when I tell you to do so. However, you don't need to turn it on until that time unless you have difficulty hearing me. You have a red emergency stop button next to you which will rapidly stop the AGS. You are not supposed to use the button in the case of nausea, because it will make you feel worse by stopping quickly. Tell me if you feel nauseous and want to relax before continuing or want to stop the experiment. Use the button only in the case of an emergency. Do you remember the two sequences you will be performing? Do you have any questions?

Day 3 of Rotation

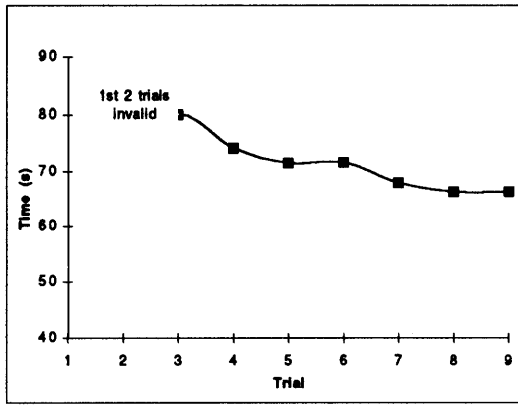
You will be performing the same practice, baseline, rotation, and post-rotation sequences as you did 5 days ago. The object is still to go as fast as you can without dropping too many blocks or putting them in the wrong place. Remember that if blocks

fall, just keep on going and pretend they are there if you need to exchange the fallen block with another block. Also, do not move your head because sudden head movements may make you nauseous while rotating. If blocks fall while rotating and you cannot recover them without moving your head, just leave them where they are and get a replacement from the box to your right. You will be given short rest periods of 1 minute or 30 seconds after each sequence to allow your arms to rest so they will not be fatigued by the end of the sessions.

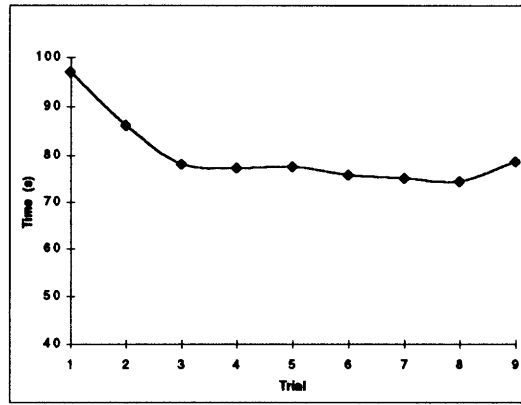
You will put the power switch of your headset to voice activation "VOX" when I tell you to do so prior to rotating. However, you don't need to turn it on until that time unless you have difficulty hearing me. You have a red emergency stop button next to you which will rapidly stop the AGS. You are not supposed to use the button in the case of nausea, because it will make you feel worse by stopping quickly. Tell me if you feel nauseous and want to relax before continuing or want to stop the experiment. Use the button only in the case of an emergency. Do you remember the two sequences you will be performing? Do you have any questions?

Appendix E: Subject Training Curves

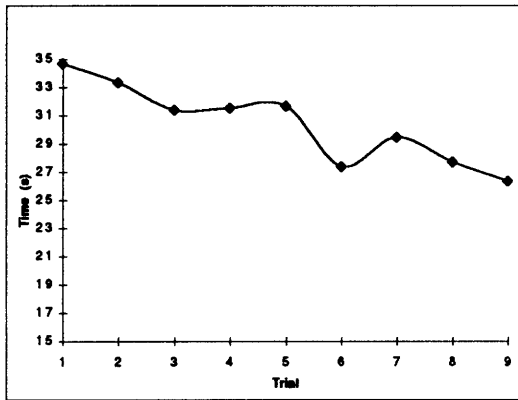
Original Training Curves



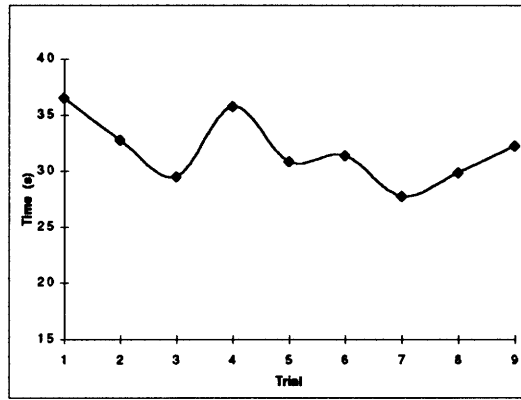
Subject A, Sequence A Original Training Curve



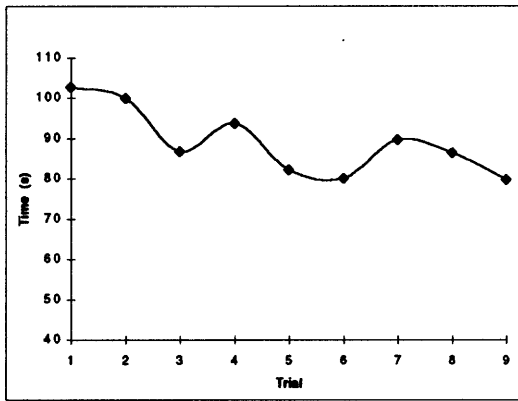
Subject B, Sequence A Original Training Curve



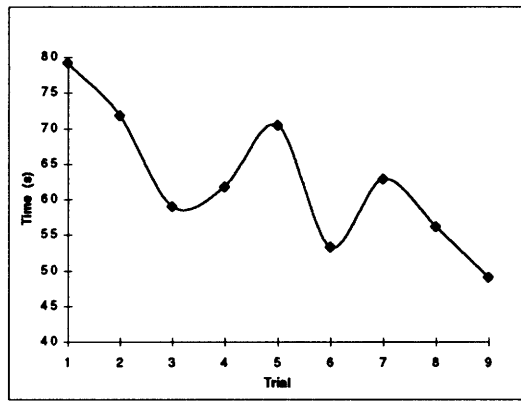
Subject A, Sequence B Original Training Curve



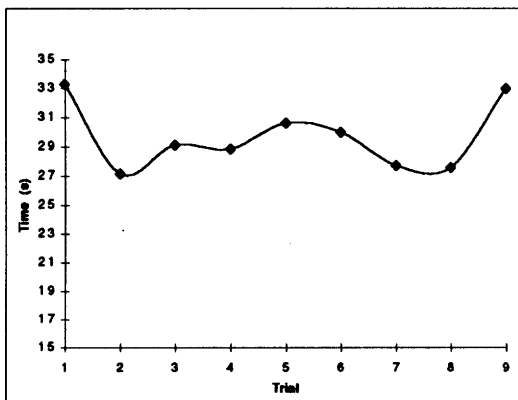
Subject B, Sequence B Original Training Curve



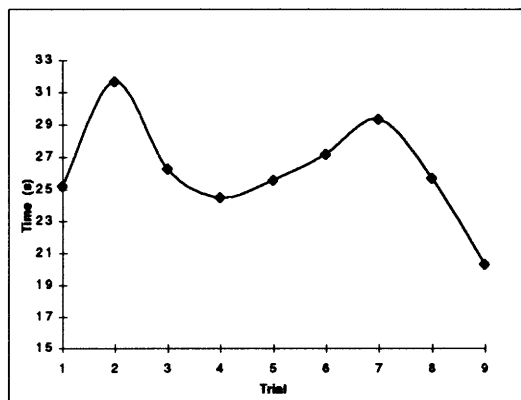
Subject C, Sequence A Original Training Curve



Subject D, Sequence A Original Training Curve

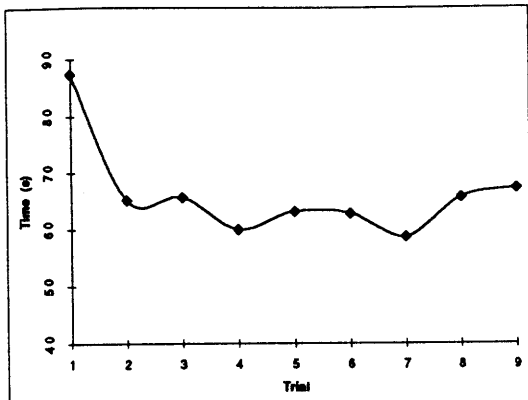


Subject C, Sequence B Original Training Curve

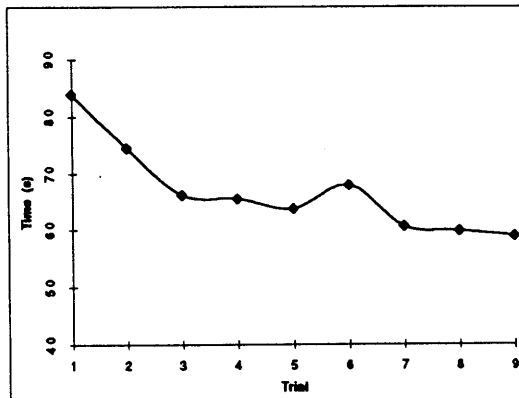


Subject D, Sequence B Original Training Curve

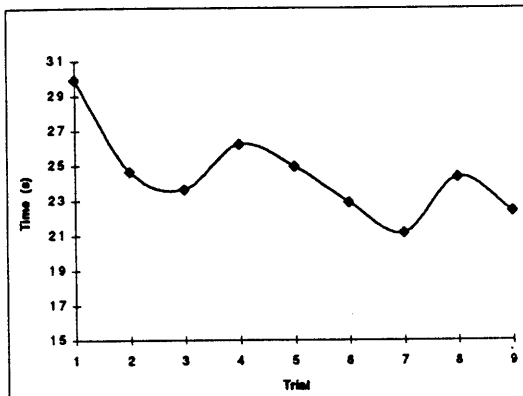
Original Training Curves



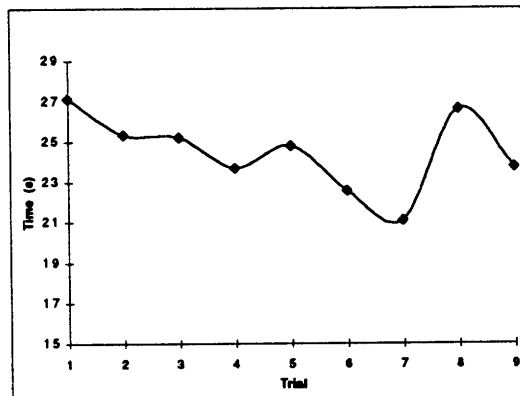
Subject E, Sequence A Original Training Curve



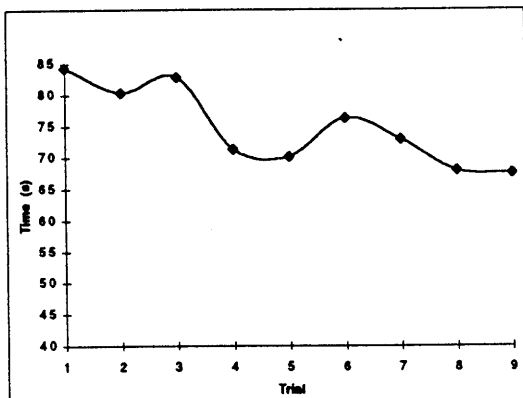
Subject F, Sequence A Original Training Curve



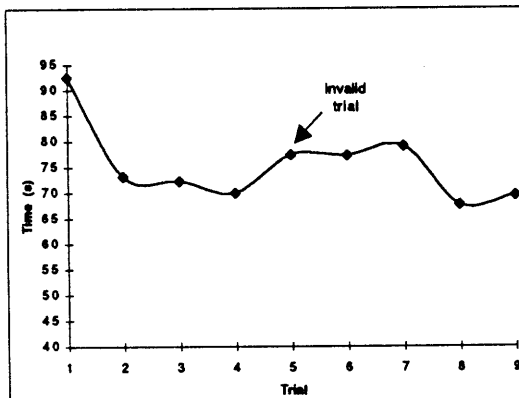
Subject E, Sequence B Original Training Curve



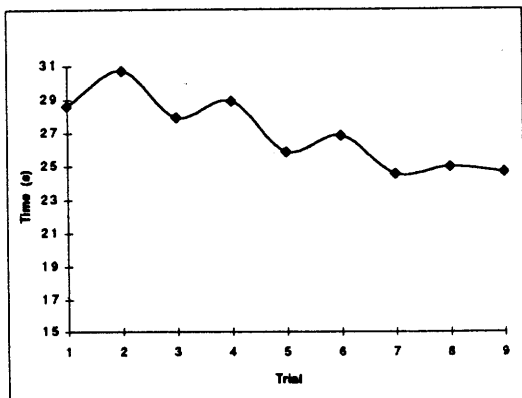
Subject F, Sequence B Original Training Curve



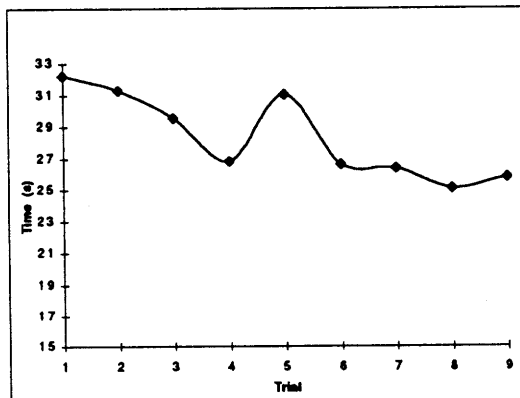
Subject G, Sequence A Original Training Curve



Subject H, Sequence A Original Training Curve

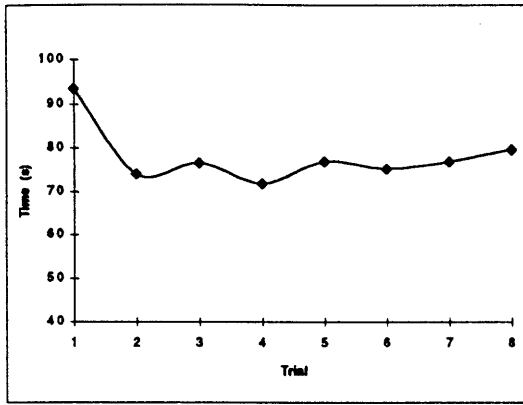


Subject G, Sequence B Original Training Curve

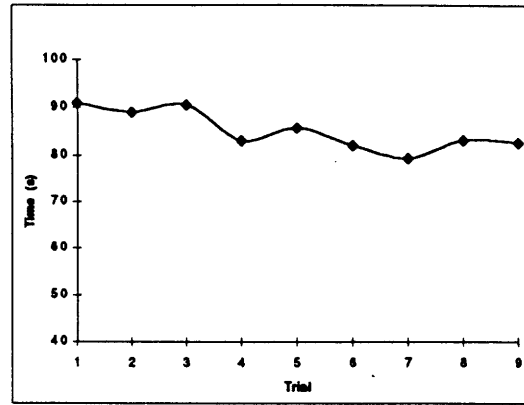


Subject H, Sequence B Original Training Curve

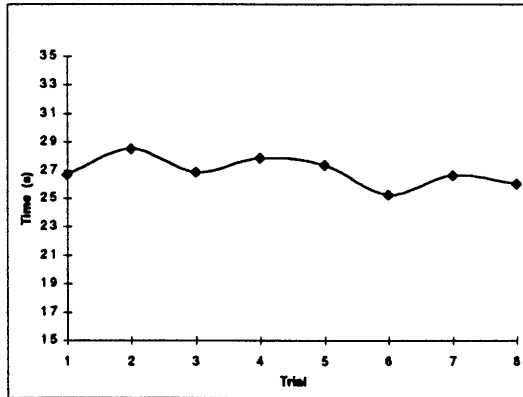
Original Training Curves



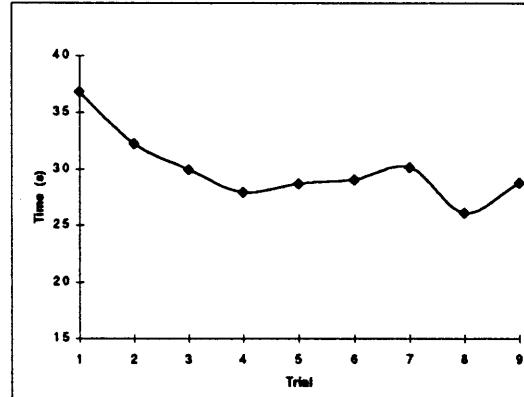
Subject I, Sequence A Original Training Curve



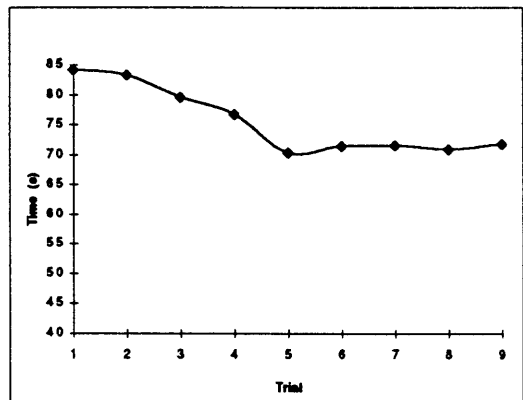
Subject J, Sequence A Original Training Curve



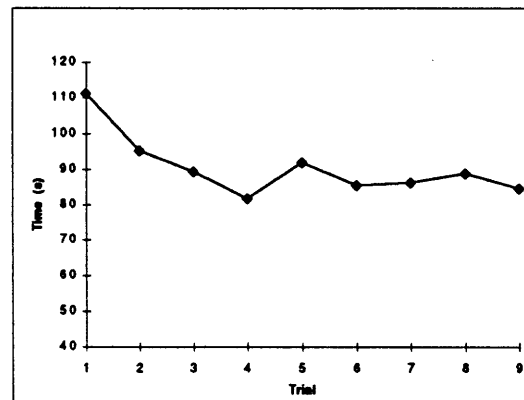
Subject I, Sequence B Original Training Curve



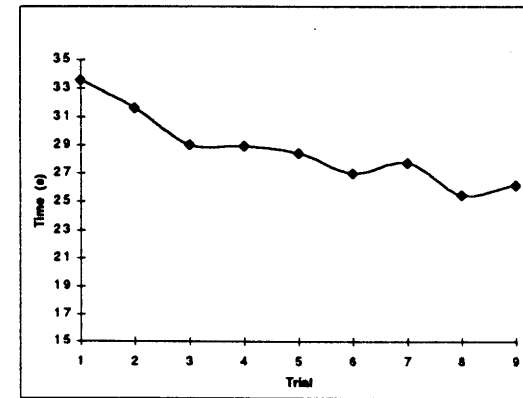
Subject J, Sequence B Original Training Curve



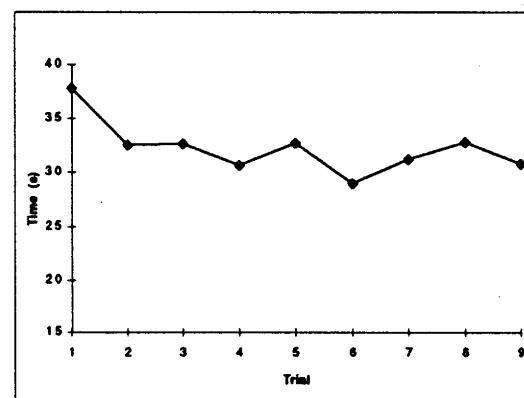
Subject K, Sequence A Original Training Curve



Subject M, Sequence A Original Training Curve

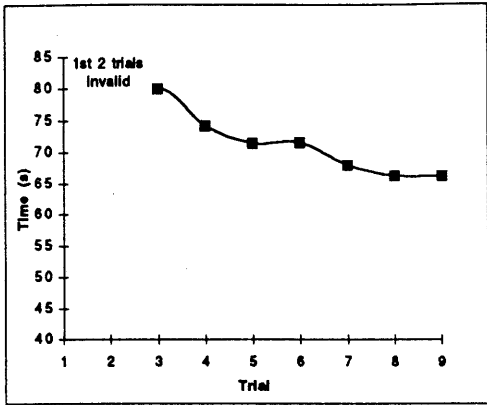


Subject K, Sequence B Original Training Curve

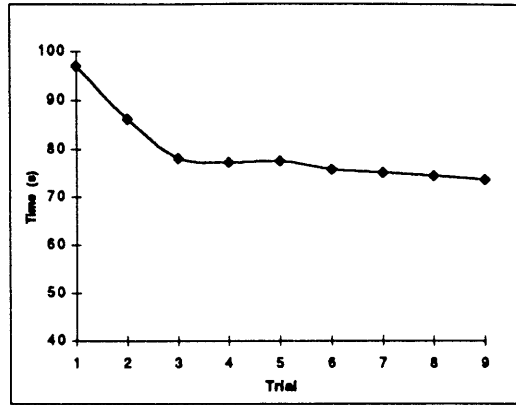


Subject M, Sequence B Original Training Curve

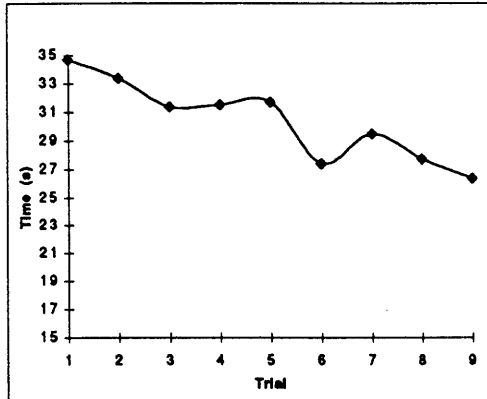
Adjusted Training Curves



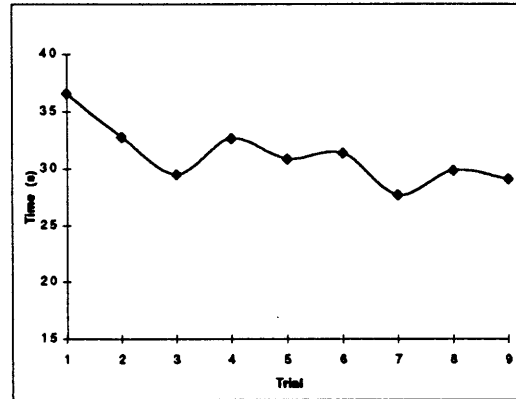
Subject A, Sequence A Adjusted Training Curve



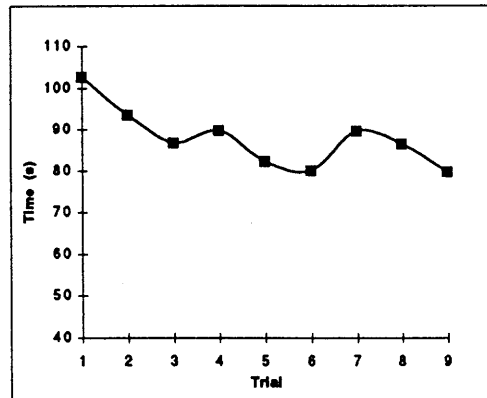
Subject B, Sequence A Adjusted Training Curve



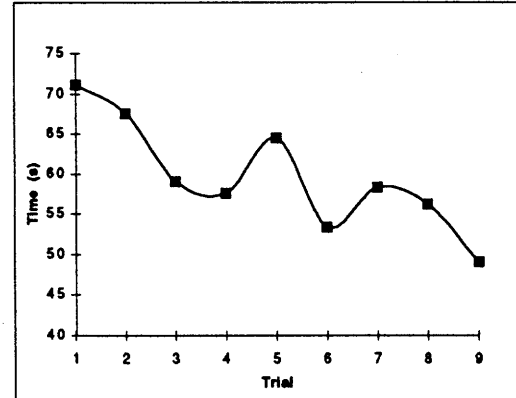
Subject A, Sequence B Adjusted Training Curve



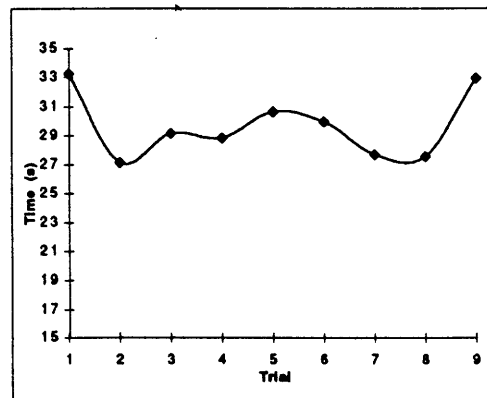
Subject B, Sequence B Adjusted Training Curve



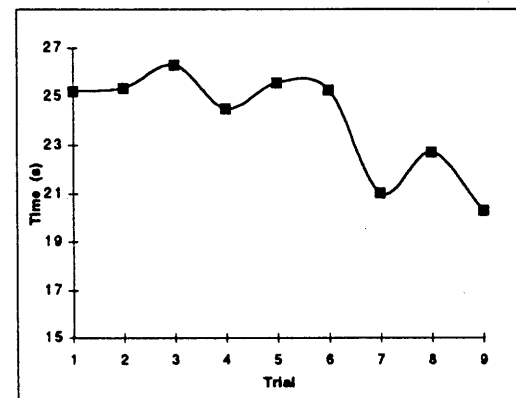
Subject C, Sequence A Adjusted Training Curve



Subject D, Sequence A Adjusted Training Curve

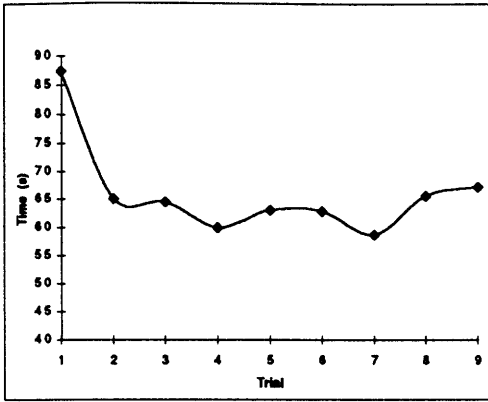


Subject C, Sequence B Adjusted Training Curve

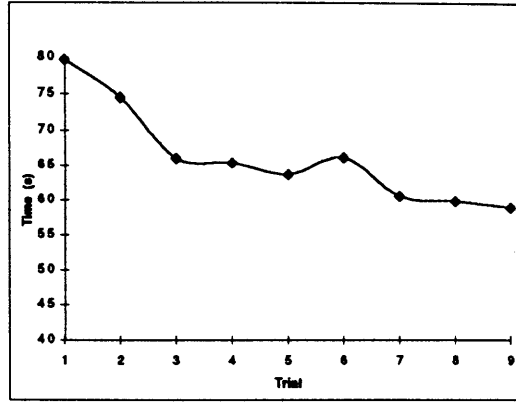


Subject D, Sequence B Adjusted Training Curve

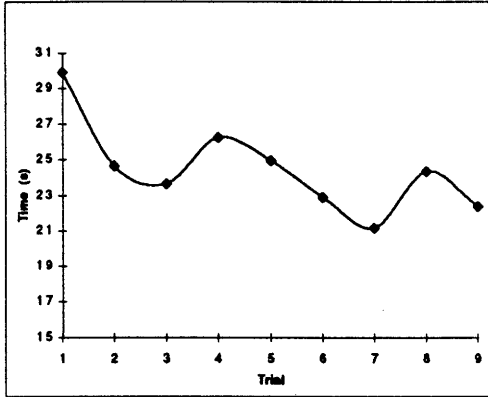
Adjusted Training Curves



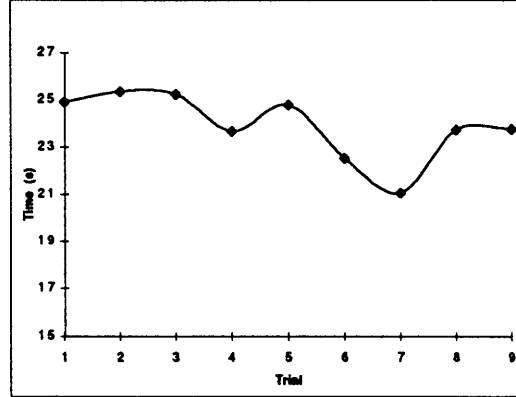
Subject E, Sequence A Adjusted Training Curve



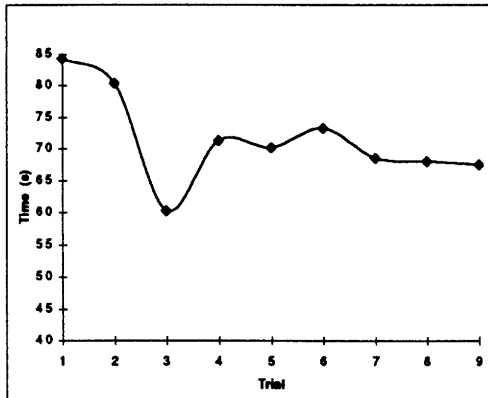
Subject F, Sequence A Adjusted Training Curve



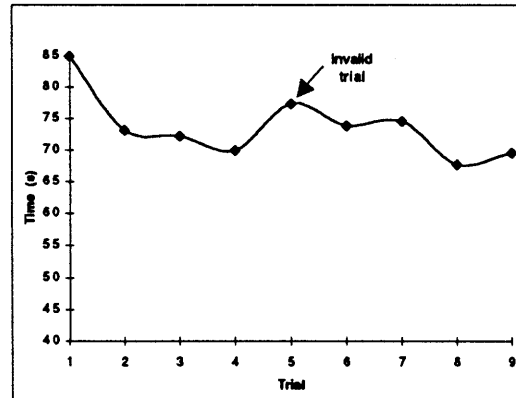
Subject E, Sequence B Adjusted Training Curve



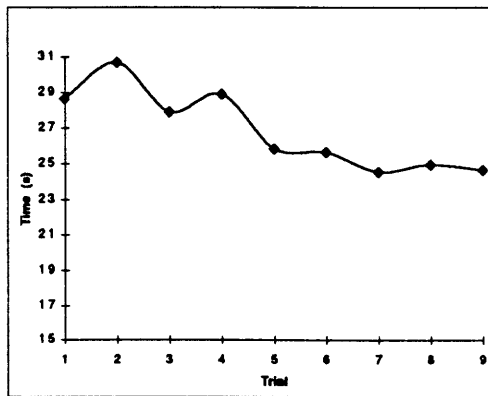
Subject F, Sequence B Adjusted Training Curve



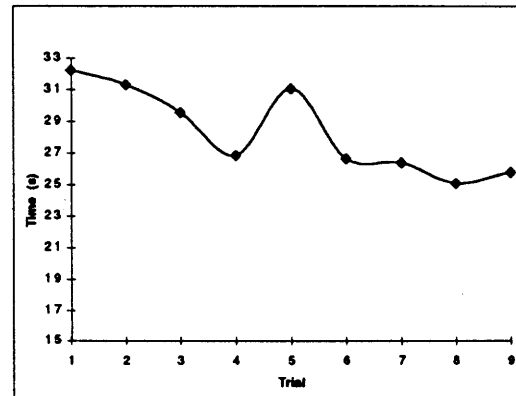
Subject G, Sequence A Adjusted Training Curve



Subject H, Sequence A Adjusted Training Curve

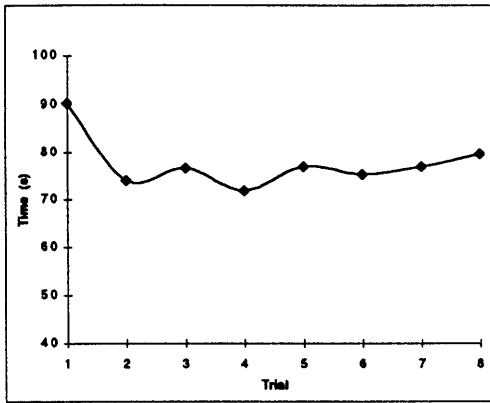


Subject G, Sequence B Adjusted Training Curve

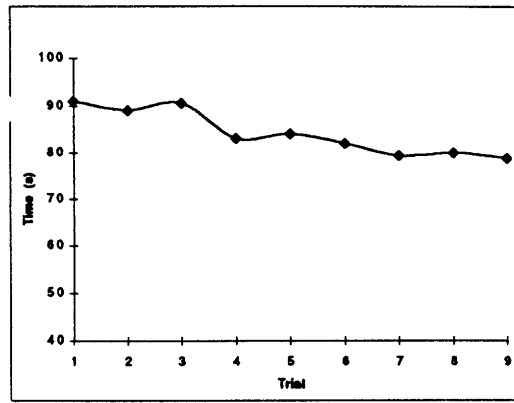


Subject H, Sequence B Adjusted Training Curve

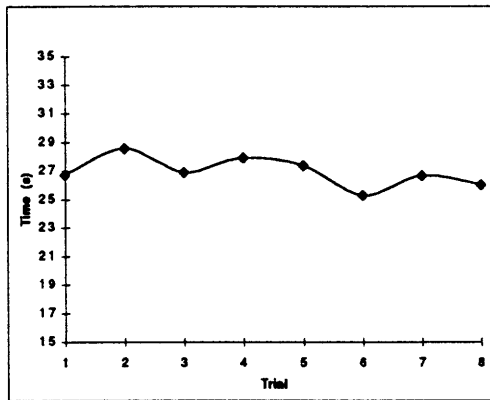
Adjusted Training Curves



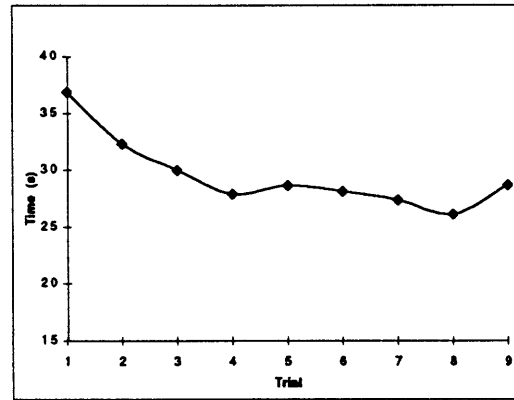
Subject I, Sequence A Adjusted Training Curve



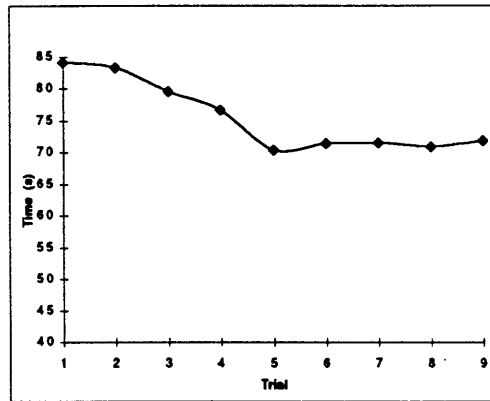
Subject J, Sequence A Adjusted Training Curve



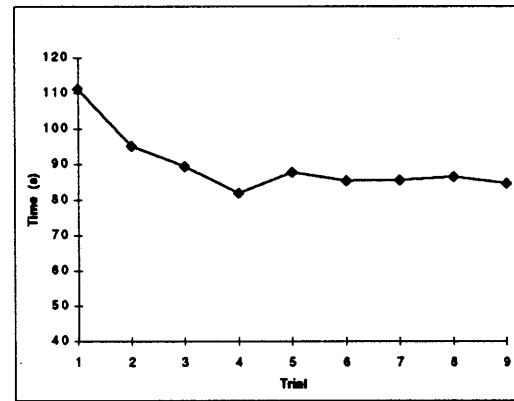
Subject I, Sequence B Adjusted Training Curve



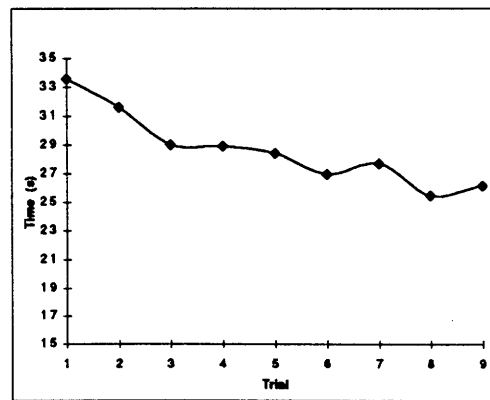
Subject J, Sequence B Adjusted Training Curve



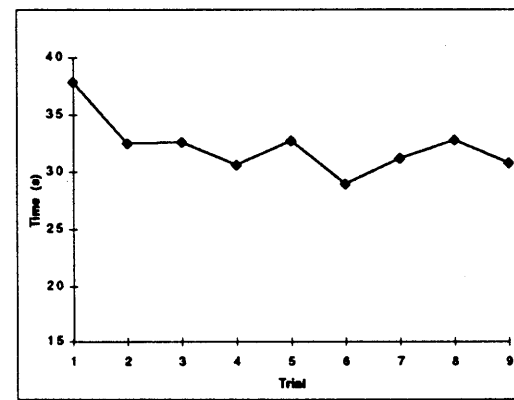
Subject K, Sequence A Adjusted Training Curve



Subject M, Sequence A Adjusted Training Curve

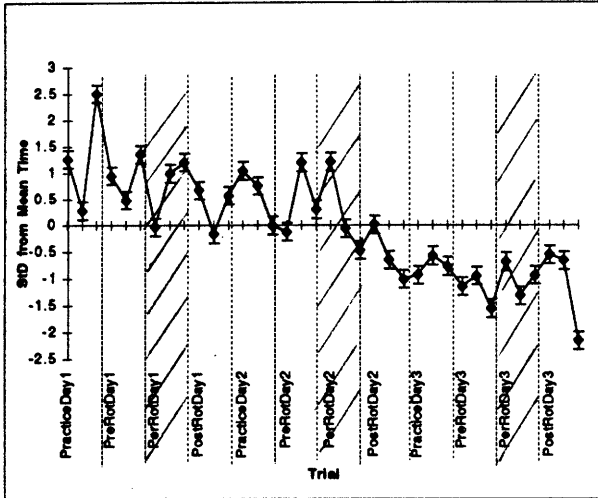


Subject K, Sequence B Adjusted Training Curve

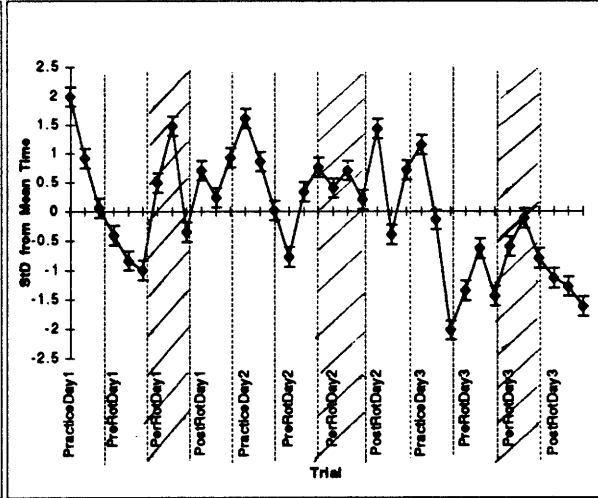


Subject M, Sequence B Adjusted Training Curve

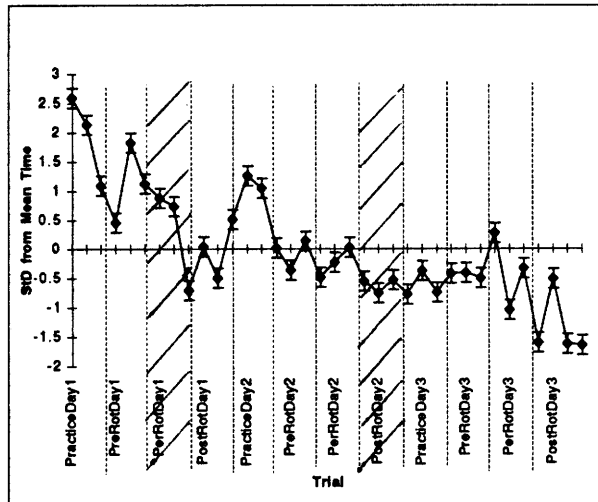
Appendix F: Normalized Plots of Subject Trial Times in Chronological Order



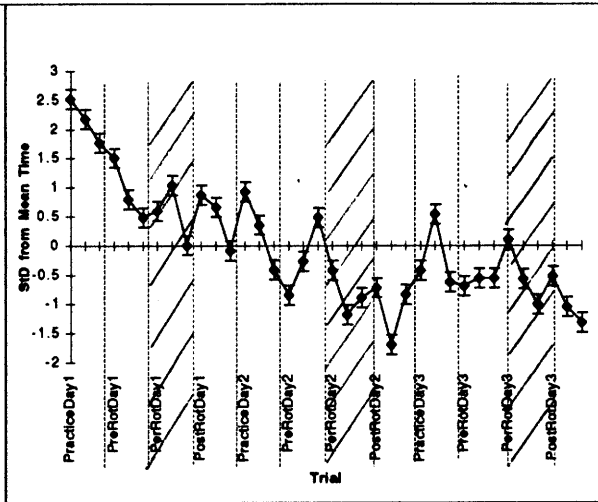
Subject A Normalized in Temporal Order of Seq A Trials



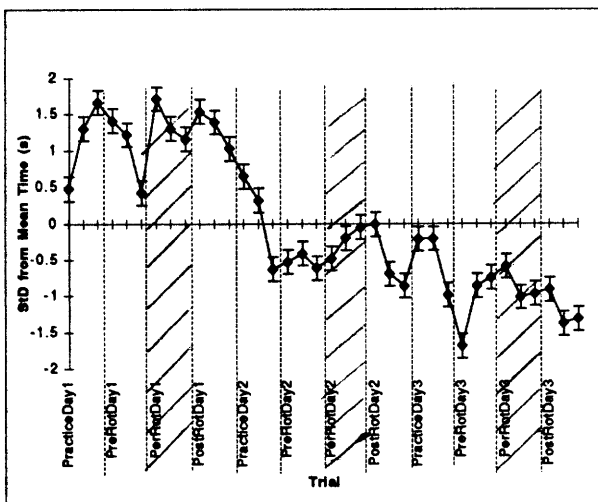
Subject B Normalized in Temporal Order of Seq A Trials



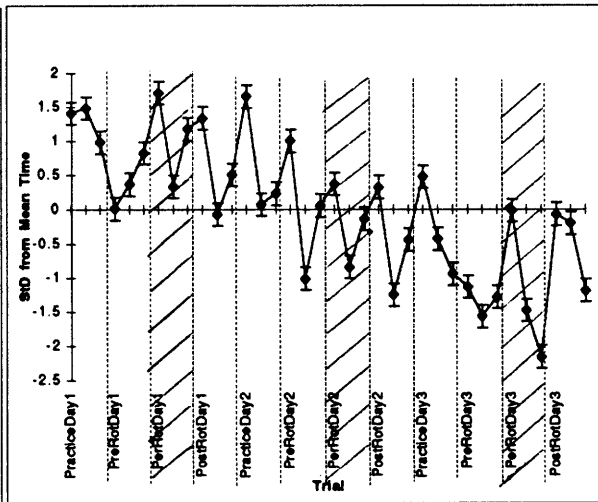
Subject C Normalized in Temporal Order of Seq A Trials



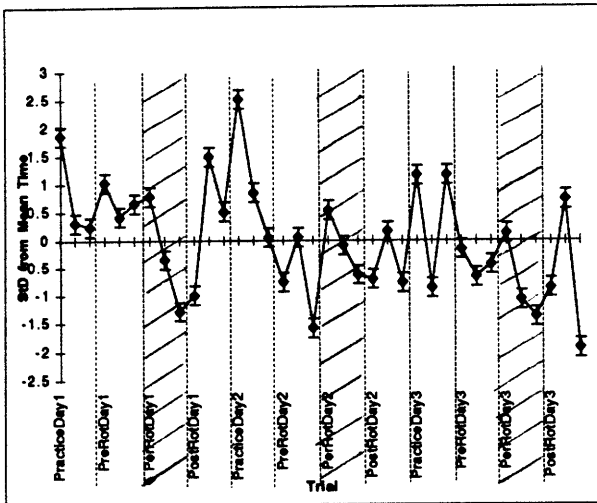
Subject D Normalized in Temporal Order of Seq A Trials



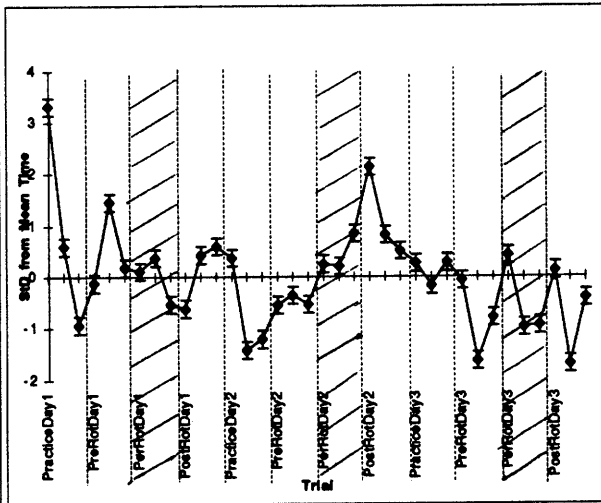
Subject E Normalized in Temporal Order of Seq A Trials



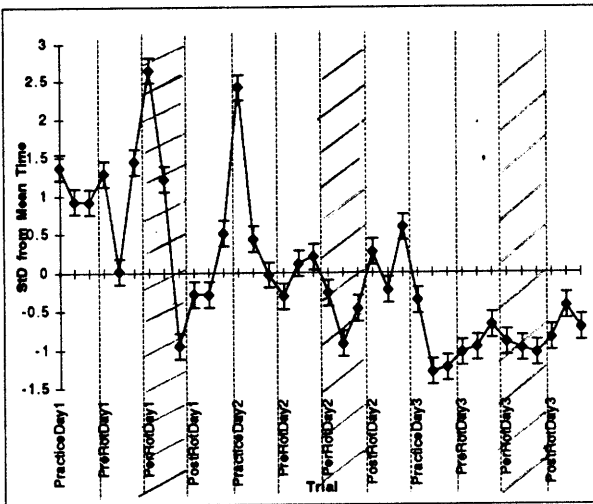
Subject F Normalized in Temporal Order of Seq A Trials



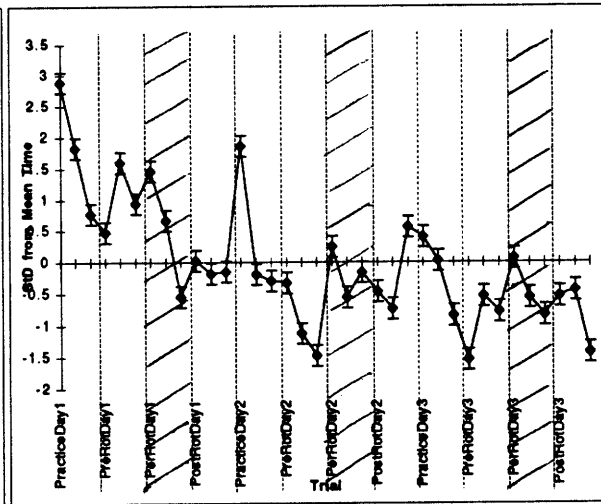
Subject G Normalized in Temporal Order of Seq A Trials



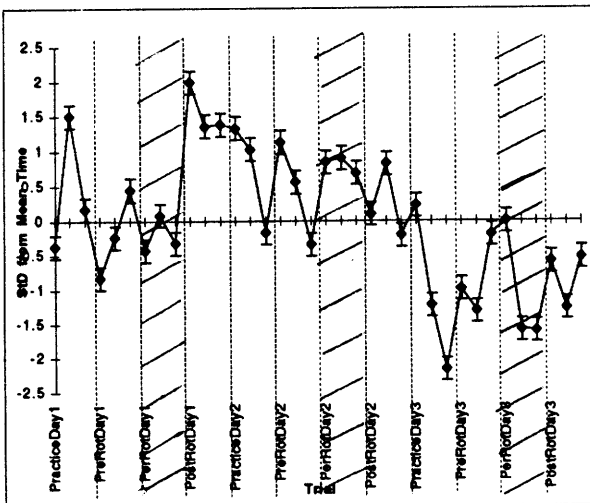
Subject H Normalized in Temporal Order of Seq A Trials



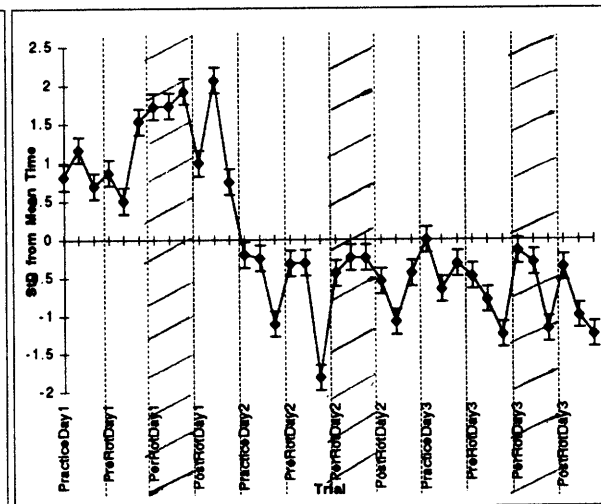
Subject I Normalized in Temporal Order of Seq A Trials



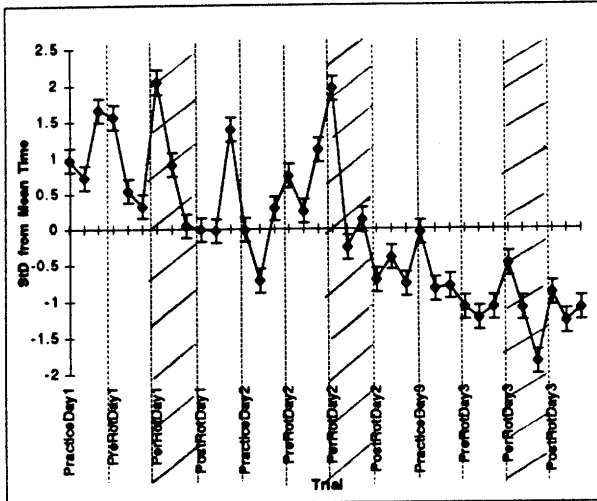
Subject J Normalized in Temporal Order of Seq A Trials



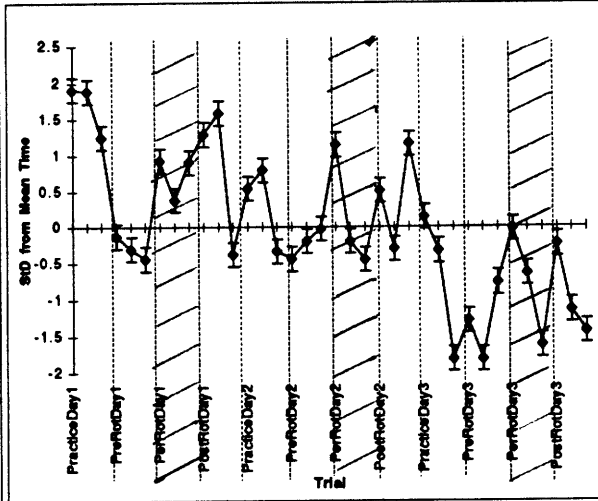
Subject K Normalized in Temporal Order of Seq A Trials



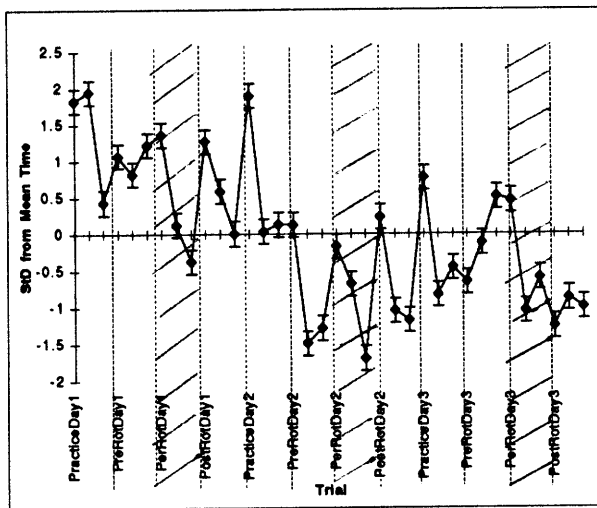
Subject M Normalized in Temporal Order of Seq A Trials



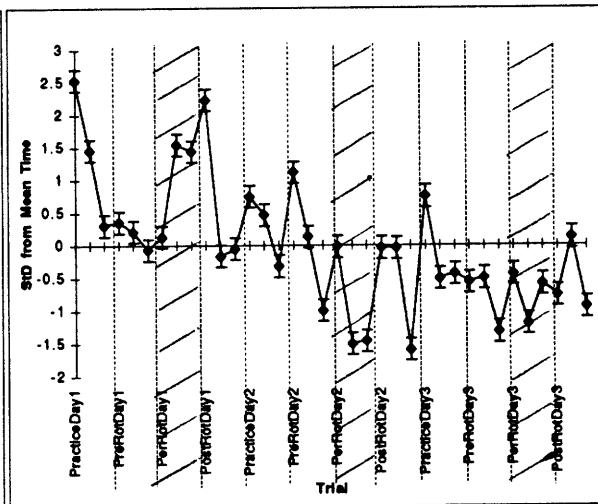
Subject A Normalized in Temporal Order of Seq B Trials



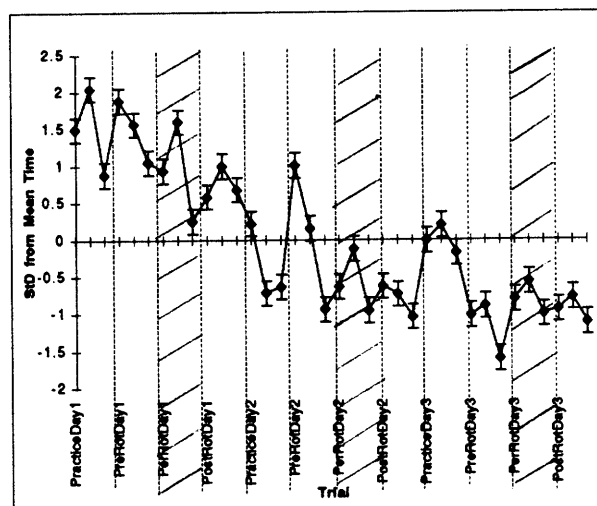
Subject B Normalized in Temporal Order of Seq B Trials



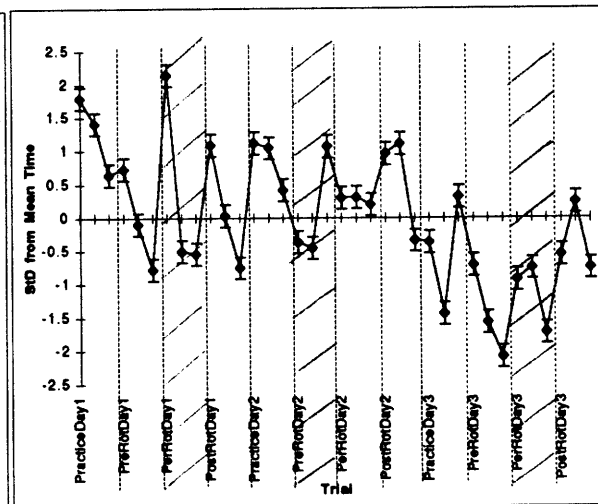
Subject C Normalized in Temporal Order of Seq B Trials



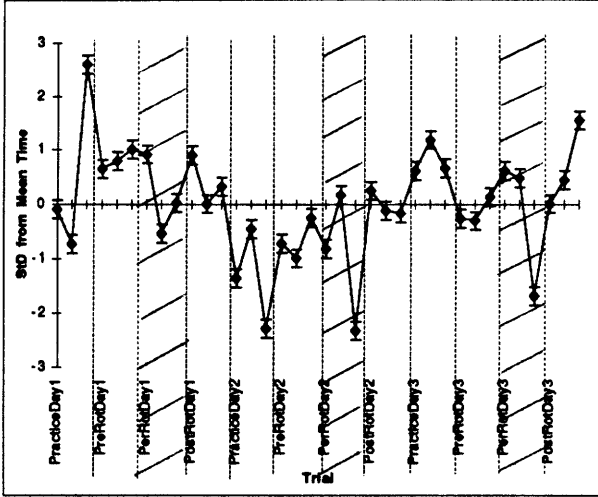
Subject D Normalized in Temporal Order of Seq B Trials



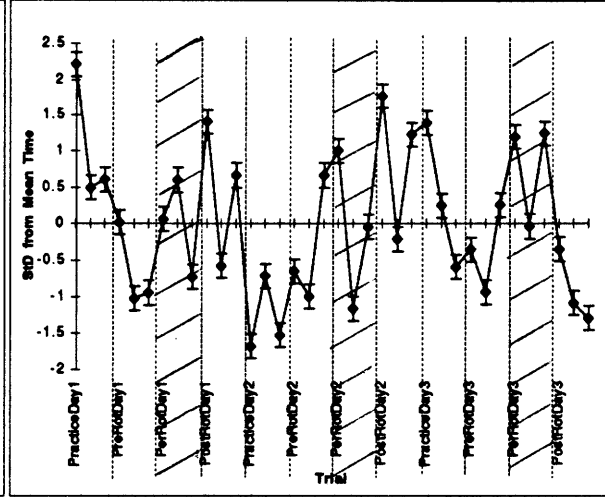
Subject E Normalized in Temporal Order of Seq B Trials



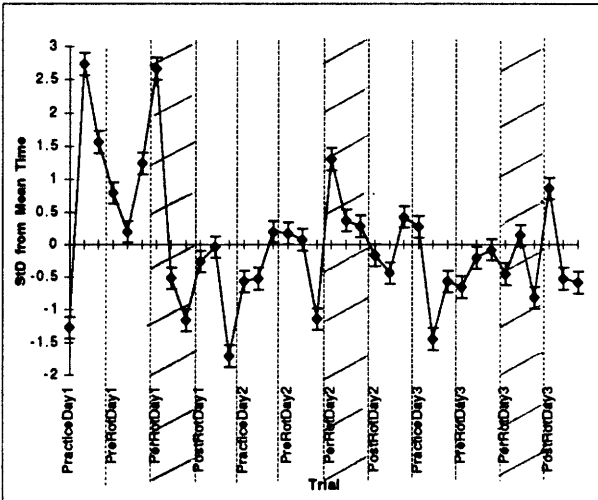
Subject F Normalized in Temporal Order of Seq B Trials



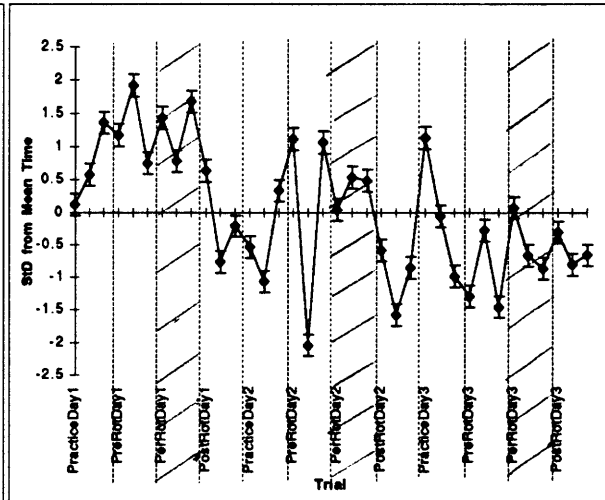
Subject G Normalized in Temporal Order of Seq B Trials



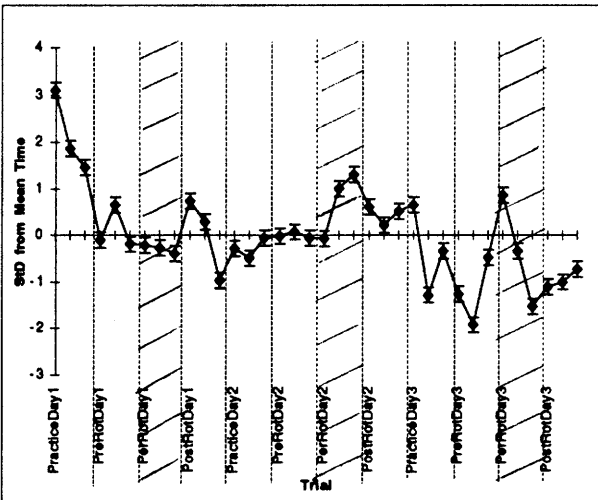
Subject H Normalized in Temporal Order of Seq B Trials



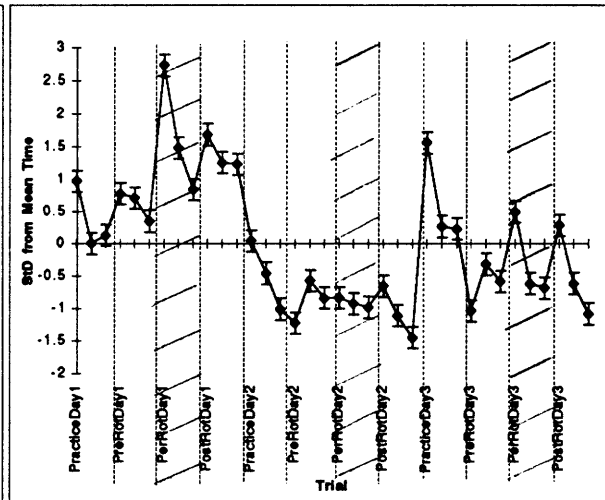
Subject I Normalized in Temporal Order of Seq B Trials



Subject J Normalized in Temporal Order of Seq B Trials



Subject K Normalized in Temporal Order of Seq B Trials



Subject M Normalized in Temporal Order of Seq B Trials