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Adaptation in artificial gravity environments

Principal Investigator

James R Lackner PhD
Ashton Graybiel Spatial Orientation Laboratory
Brandeis University, MS033
Waltham, MA 02454
Tel: 781-736-2033
Fax: 781-736-2031
Email: lackner@brandeis.edu

Co-Investigatos:

DiZio, Paul
Ashton Graybiel Spatial Orientation Laboratory

Objective

The objective of the proposed research is to provide a technical base for evaluating the feasibility of a rotating "artificial gravity" environment for long-duration space missions. We previously demonstrated that Coriolis forces generated during rotation at 10 rpm disrupt head and arm movements but adaptation is possible. Our goals were to study (1) the rotation rates up to which adaptation is possible, (2) whether measurements of disruptions caused by rotation and subsequent adaptation in 1-G underestimate or overestimate the effects to be expected during rotation in environments with a background force level less than 1-G, and (3) how the magnitude and orientation of the background force affect retention and transfer of adaptation to rotation. Our studies will: (1) result in recommendations regarding design criteria for artificial gravity environments; (2) provide sound scientific reasons for establishing confidence limits on the recommendation; (3) provide a basis for designing preadaptation procedures to alleviate expected problems in a rotating space vehicle; and (4) enhance basic understanding of spatial orientation on Earth.

Background

This is the third and final report for a three-year project which ended in FY01. Results from Year 1 of the project indicated that subjects can adapt readily to rotation rates up to 10 rpm. Year 2 focused on 1) how to suppress the disorientation and movement disruptions that occur before adaptation to a new force environment is complete, and 2) how to circumvent such transient disruptions by context specific adaptation. Previous reports have covered these results in detail. The new results for Year 3 dealt 1) whether measurements of the movement errors caused by rotation in a 1 g force background predict errors in non-1g backgrounds and 2) whther adaptation to rotation acquired in 1 g transfers to non-1 g force backgrounds. For this final report, the results from the first two years are capsulized below (items 1 & 2), in addition to the new results for Year 3 (items 3-6).

Results

1) Accuracy of reaching movements made at 10 rpm in a 1 g force background level. (Year 1) These experiments were conducted with the subjects seated at the center of rotation with the start position of their hand right at the center of rotation. The resultant gravitoinertial force on the subject's hand was 1g at the start of a movement during rotation and about 1.00076g at the end of a movement terminating 35 cm from the center of rotation because of the centrifugal "force" present off-center. During rotation, the gravitoinertial force on the otolith organs increased from 1g to 1.00006g. Prior to rotation, subjects reached in essentially straight lines (viewed from above) to the targets. During the first several movements made at constant velocity rotation, subjects reached in curvilinear paths and their movements ended far from the

targets in the direction of the Coriolis forces that had been generated during the movements. These reaching movements have a bell shaped velocity profile, consequently the Coriolis force generated during a movement also had a bell shaped profile. As can be seen from the figure, the movement path becomes progressively deflected as the forward velocity of the arm increases then returns somewhat as the movement slows and the Coriolis force abates but still ends far away from the target position. These types of measurements are the first systematic, quantitative assessments of movement paths and accuracy during exposure to rotation. They demonstrate functionally significantly degradations of movement control during initial exposure to rotation at 10 rpm. The size of the initial changes in movement curvature and endpoints was the same for subjects tested with and without visual feedback about pointing accuracy.

2) How many movements does it take to regain accurate reaching? (Year 2) Subjects who continue to make reaching movement to the target position show progressive increases in movement accuracy and their movement paths become less curved. Subjects who are tested in darkness regain baseline accuracy and straight movement paths within about 20 reaches even though they do not receive visual or tactile feedback about their reaching accuracy. Subjects tested with the room lights on adapt more quickly being back to pre-rotation baseline levels in five to ten movements on average. These results demonstrate that adaptation to Coriolis force perturbations of reaching movements is remarkable rapid if subjects repeat the goal directed movements. This finding was totally unexpected in the light of earlier qualitative studies suggesting inability to adapt to rotation at 10 rpm. We made yet another interesting observation that led us to perform a "satellite" series of experiments. We found that if subjects were tested in darkness (the target LED went out as they lifted their finger) and attempted to point just above the apparent location of the target not letting their pointing finger touch the Plexiglas surface, then the absence of terminal contact of the hand resulted in a disruption of adaptation. Subjects over time regained straight movement paths but they did not regain full movement endpoint accuracy after 40 movements, still being off by about 50% of the initial error. This finding suggested that contact of the hand was a critical factor in adaptive control of movement and led us to do a series of experiments demonstrating that light contact of the index finger has a profoundly stabilizing influence on postural control..

The first few post-rotation movements are always mirror images to the first reaches made during rotation. This is interesting because when subjects have fully adapted to Coriolis forces during rotation, they reach in straight lines accurately to the target location. The character of the aftereffect indicates that the adaptive compensation achieved consists of precisely coordinated motor innervations that exactly predict and cancel the Coriolis forces generated by the forward velocity of the arm. These findings indicate that the nervous system has developed an internal model of the altered demands for control of the exposed limb. A key issue of ongoing and future work concerns the generality of such a model, e.g. whether it is limb specific, and whether exposure paradigms can be developed that allow a model of the new force environment per se to be generated so that all body movements could again be executed accurately.

3) Influence of background force level on initial errors in reaching movements (Year 3). We have conducted two sets of experiments on this issue, one in our slow rotation room and the other in the 0g phase of parabolic flight maneuvers. In the slow rotation room study, the subjects were seated 2.6 m from the center of rotation. At 10 rpm, this led to a .25g centrifugal force on the hand, leading to a net 1.031g vector on the hand compared to 1g at the center of rotation. The subjects pointed to targets without receiving visual feedback about the accuracy of their movements. The Coriolis forces generated by their movements was comparable to that of subjects pointing while seated at the center of rotation, about .2g. It is important to note that the magnitude and direction of the Coriolis force depends only on the velocity of the arm in relation to the plane of rotation and the velocity of rotation. Consequently, if a subject points to the same target while at the center and while in the periphery of the slow rotation room turning at 10 rpm, the Coriolis force on the arm will be the same for the same velocity arm movement. Our results indicate comparable trajectory deviations and endpoint errors for subjects seated on-center and off-center. The subjects who were tested in parabolic flight were seated in a rotating chair that could be maintained at constant velocity regardless of background force level variations. The chair was equipped with a Plexiglas work space comparable to that on the test chair in the slow rotation room experiments. An OPTOTRACK movement analysis system was used to record both arm movements and chair position. Pre-rotation baseline movements were made both in straight-and-level flight and in the 0g phases of the first several parabolas. The chair was then accelerated to constant velocity. After a minimum delay of two minutes, the subject began making reaching movements in the 0g phase of the next parabola and continued to do so in

the 0g phase of the next ten parabolas. The subject's movements were made to a beep that signaled him to start the movement. The beeps were timed so that the subject would be in view of the OPTOTRACK cameras when he reached. The same cadence and spacing and number of movements - 4 per parabola - was maintained in pre-, per-, and post-rotation conditions. In these flight studies, it was not possible to use a visual target that would be extinguished on movement onset and have the movement completed in darkness. Consequently, we blindfolded the subjects and had them point to a position on the Plexiglas surface that they felt was in their midline. This proved easy for them to attempt. The experimental findings indicated that the pre-rotation baselines are more variable in 1g straight-and-level flight as well as in 0g than under ground-based conditions. Interestingly, the per-rotation reaching movements in 0g overall show less trajectory curvature and smaller endpoint errors than in 1g on-center rotation. Both types of deviations are about 40% smaller than under 1g conditions for the same levels of Coriolis force perturbations.

4) Influence of background force level on the rate and magnitude of adaptation (Year 3). Although force background did not affect the magnitude of the curvature changes or endpoint errors, on-center versus off-center in the slow rotation room, it greatly affected the patterns of adaptation. Restoration of straight-line reaches, that is adaptation of movement curvature, occurred in both situations but required more movements to fully achieve in the increased gravitoinertial force condition. By contrast, endpoint adaptation took much longer in the increased force condition and approached 50% after 20 movements and then showed no further change. Consequently, these off-center test subjects then reached in straight paths to the wrong place. Studies currently underway indicate that fuller adaptation is achieved when visual feedback about reaching accuracy is provided. The parabolic flight observations show that adaptation rate, in terms of number of movements to achieve straight paths and accurate endpoints, proceeds at about the same rate as in 1g. As mentioned above, the initial curvature deviations and endpoint errors are smaller in 0g than in 1g. However, the 0g post-rotation aftereffects show the opposite pattern. The aftereffects are nearly double in size to that of the initial curvature and endpoints errors; in fact, they are larger than the aftereffects we have seen in 1g test conditions, on-center. These results are consistent across each of the four subjects we have been able to test so far in parabolic flight. In up coming experiments, we will be able to test subjects under 1.8g conditions as well. This information will be crucial in interpreting the 0g observations.

5) Do adaptive changes in movement control achieved during rotation in one background force level transfer to rotation in a different force level? (Year 3). Previously, we showed that in 0g and 1.8g force backgrounds, as well as in a normal 1g environment, it is possible to rapidly adapt to the deviations in reaching endpoint and trajectory curvature caused initially by Coriolis forces in a rotating environment. Our new findings are that subjects who adapt to Coriolis forces in a 1g environment showed full transfer to 0g or 1.8g environments, in parabolic flight. This means pre-adaptation training in 1g on the ground to ameliorate the side effects of a rotating artificial gravity environment should transfer to an operational rotating artificial gravity environment in space where the background force level will be less than 1g.

Significance

Work on rotating artificial gravity environments has enlightened us about the presence of Coriolis and other inertial accelerations on the arms and head during self-generated, voluntary movements in an artificial gravity environment and in a normal terrestrial environment. Initial measurements have shown that Coriolis forces on the hand during natural turning and reaching movements are much greater than in our rotating room experiments, yet the hand reaches its goal accurately and the Coriolis forces are not noticed. We are now examining the form of this automatic compensation for self-generated forces in a terrestrial environment. Our current work on adaptive changes in head movement control points to neck proprioceptive as well as vestibular signals being a key factor in the disorientation and motion sickness elicited by head movements during passive body rotation. We had earlier shown that simply altering the effective inertial mass of the head makes voluntary head movements provocative. These findings have significance for understanding the etiology of space motion sickness and motion sickness on Earth. They also have direct significance for understanding why cybersickness occurs in virtual environments. Almost all situations in which motion sickness occurs involve alterations in the normal patterning of eye and head movement control in relation to proprioceptive and vestibular feedback.

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