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Artificial Gravity: Head Movements During Short-radius Centrifugation

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Abstract

Short-radius centrifugation is a potential countermeasure to long-term weightlessness. Unfortunately, head movements in a rotating environment induce serious discomfort, non-compensatory vestibulo-ocular reflexes, and subjective illusions of body tilt. In two experiments we investigated the effects of pitch and yaw head movements in participants placed supine on a rotating bed with their head at the center of rotation, feet at the rim. The vast majority of participants experienced motion sickness, inappropriate vertical nystagmus and illusory tilt and roll as predicted by a semicircular canal model. However, a small but significant number of the 28 participants experienced tilt in the predicted plane but in the opposite direction. Heart rate was elevated following one-second duration head turns. Significant adaptation occurred following a series of head turns in the light. Vertical nystagmus, motion sickness and illusory tilt all decreased with adaptation. Consequences for artificial gravity produced by short-radius centrifuges as a countermeasure are discussed. © 2001 Published by Elsevier Science Ltd.

Keywords: Coriolis effects, artificial gravity, orientation illusion, heart rate, perceived motion

1. Introduction

Traditional countermeasures against the adverse effects of prolonged weightlessness, such as exercise, resistive garments and lower-body negative pressure, appear to be insufficient in practice and are often disregarded by astronauts. Artificial gravity represents a potential countermeasure that is unique. Rather than alleviating the symptoms, it attempts to remove their cause. Although long a favorite topic of scientists and science fiction authors, it is only now about to receive serious attention for space flight experiments and validation [1]. Recent task groups and countermeasure workshops conducted by NASA and the National Space Biomedical Research Institute have refocused attention on the potential use of artificial gravity (AG) as an in-flight countermeasure. It could be effective against bone and muscle loss, cardiovascular deconditioning, and neurovestibular disturbances. Unfortunately, space limitations within existing and planned vehicles demand that any AG centrifuge device tested in the foreseeable future be of limited radius (on the order of 1-3 meters). Centripetal accelerations equal to or exceeding 1-g will therefore require relatively high angular velocities (on the order of 30 rpm). As a consequence, head movements on the centrifuge that leave the plane of rotation (out-of-plane head turns) will create unexpected illusory sensations, inappropriate non-compensatory vestibulo-ocular reflexes, and motion sickness. Thus, practical use of an intermittent short-radius centrifuge for in-flight gravity treatment requires that crewmembers be capable of rapidly adapting to the unexpected canal inputs with minimal side- or after-effects. Furthermore, it will be essential to retain the astronauts' adaptation to the 0-g state in order to avoid space motion sickness each time they transition from the centrifuge to weightlessness. We report recent findings obtained with the MIT short-radius centrifuge (SRC) that encourage the use of a SRC as a viable countermeasure.

To derive some qualitative predictions about the sensory effects of out-of-plane head turns we need to understand how the latter affect the vestibular system: After rotation for more than about 30 seconds the cupulae of the semicircular canals return to the neutral position and the sensation of rotation disappears. Head movements that are executed while spinning at a constant angular velocity move the semicircular canals into and out of the centrifuge's plane of rotation. The endolymph in the respective canals deflect the cupulae, sending signals to the brain which no longer correspond to the expected head velocity signal produced during head movements in a non-rotating environment [2, 3]. The discrepancy produces illusory body tilt and causes motion sickness. It also triggers an inappropriate vestibulo-ocular reflex (VOR) about an axis perpendicular to both the axis of head movement and the AG spin axis. Illusory tilt can be experienced as crisp body rotation or as a continuous tumble of several revolutions.

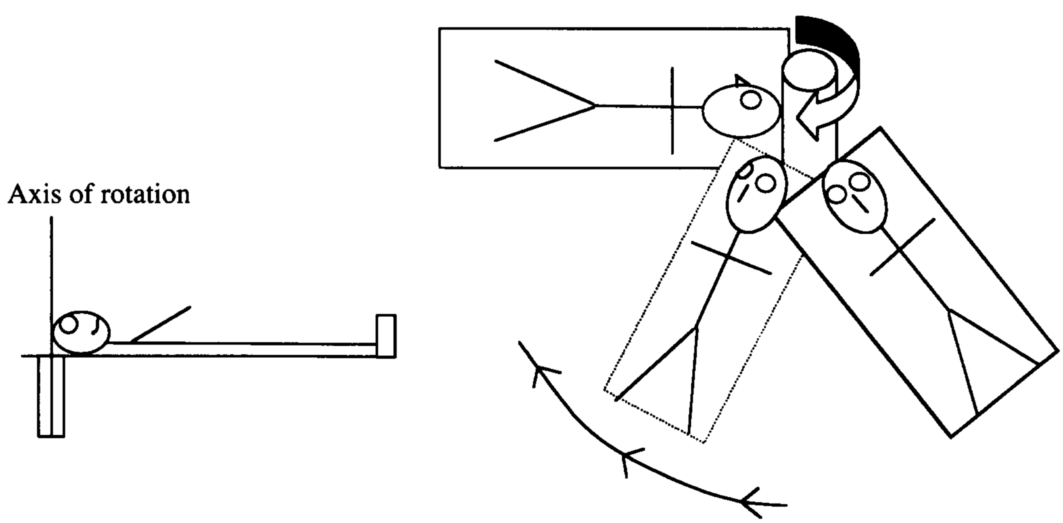
Consider a participant lying supine on a radially aligned bed rotating about a vertical axis. During a yaw head turn in a non-rotating environment, the vestibular system receives a pure yaw input. However, that same head turn conducted within a clockwise rotating environment (angular velocity vector of the centrifuge perpendicular to the head yaw axis) produces additional canal stimulation in the pitch and roll planes. These signals produce an inappropriate non-compensatory eye response in the vertical direction with respect to the yaw head movement. At slower rotation rates, up to 6-10 rpm, participants adapt to these side effects over several days of activity [4]. However, the higher rotation rate required for short-radius countermeasure purposes produces much more disturbing side effects.

We performed two studies on the MIT short-radius centrifuge (SRC). The first involved assessment of illusory tilt, motion sickness and heart rate of 20 participants during out-of-plane head movements (assessment study). The second study focused on adaptation by repeated head movements while rotating. We examined the vestibulo-ocular reflex (VOR), illusory tilt, heart rate and motion sickness (adaptation study).

2. Methods

2.1 MIT short-radius centrifuge (SRC)

The MIT SRC (Figure 1) has a two-meter radius and is designed to rotate a supine participant clockwise about an axis just above the head. The centrifuge is driven by a one-hp electric motor through a 50:1 gear reduction. A 300MHz PC Emachine running LabVIEW software (version 5.1) was used to generate velocity profiles and control the velocity of the centrifuge. A Hewlett Packard optical encoder (256CPR) mounted to the centrifuge provided accurate velocity readings. The centrifuge was operated at 23 rpm, which created a 1-g force at the feet of a 1.68-meter tall participant. A 32-channel slip ring located in the center of the support structure was used to transmit data from the centrifuge to the data acquisition system. An on-board RCA color video camera mounted to one end of the centrifuge and wired through the slip ring provided real-time images of the participant during centrifugation.



<u>Figure 1</u>: Left panel: Participant positioned supine on the MIT SRC during clockwise centrifugation. Right panel: Top view of an exemplar yaw head movement from right-ear-down (at the right) to nose-up (when the feet are pointing to the left).

Additional Equipment

An ISCAN eye-imaging system measured the displacement of the corneal reflex, and allowed us to assess the reflexive eye movements resulting from out-of-plane head turns during centrifugation. Watson inertial angular rate sensors measured the angular velocity of the participant's head about the yaw and pitch axes. The ISCAN eye imaging goggles and Watson angular rate sensors were powered by on-board batteries and wired through the slip ring. A 300MHz PC Emachine was used for ISCAN data collection, two monitors and a VCR were used to view and record eye movements. Another video camera was used to view the participant during centrifugation, and a VCR recorded head movements made in the light. To enable clear communication with the participant during the experiment, Motorola TalkAbout two-way radios were used. An Acumen TZ-Max 100 heart rate monitor measured the heart rate. Average heart rate was sampled every five seconds, as computed from beat-to-beat measurements derived from electrocardiograph electrodes. A windshield canopy that covered the entire length of the centrifuge was darkened with black cloth to prevent light cues during pre- and post-adaptation phases of the adaptation study.

2.2 Participants

Twenty-eight participants (14 male, 14 female) selected from the MIT Department of Aeronautics and Astronautics student population participated in the studies. Twenty participants (10 male, 10 female) participated in the assessment study and the remaining eight participants (4 male, 4 female) participated in the adaptation study. Applicants completed a medical questionnaire and were screened for disqualifying medical conditions (including symptoms of vestibular abnormalities), and previous artificial gravity training. Participants ranged in age from 18 to 32 years. They were instructed to abstain from consuming caffeine and alcohol for 24 and 48 hours preceding the experiment, respectively. The experimental protocols for both studies were approved by the MIT Committee on the Use of Humans as Experimental Subjects.

2.4 Design and Procedure

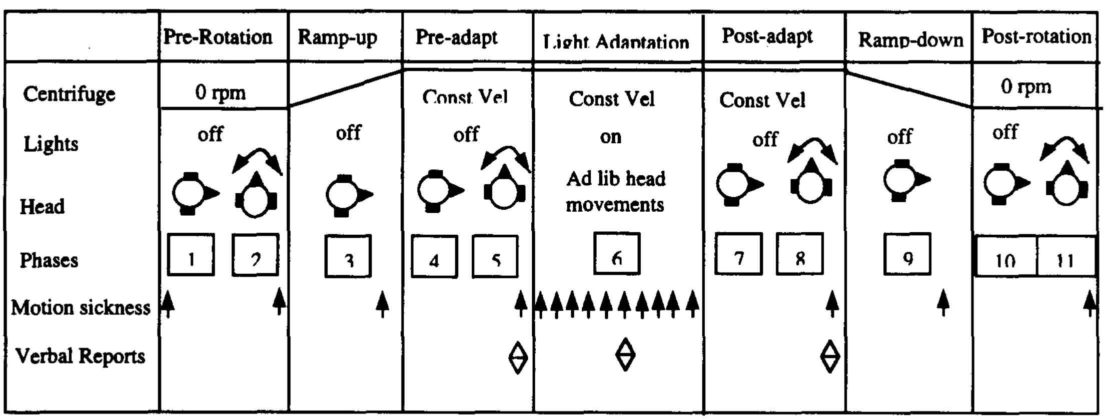
2.4.1 Assessment Study

This study investigated the direction and magnitude of illusory body tilt, the persistence of illusory sensations, heart rate and motion sickness, resulting from yaw and pitch head turns during clockwise centrifugation [5]. Participants were fitted with the heart rate monitor and positioned supinely on the centrifuge. To eliminate visual cues, participants wore a blindfold and all of them reported complete darkness. The centrifuge was accelerated at $6^{\circ}/sec^2$ until a constant angular velocity of 23 rpm was achieved.

Every 20 seconds, participants made yaw head movements on the experimenter's cue. Four sets of head movements were made to the right (clockwise yaw) and four to the left (counterclockwise yaw). Each set consisted of a 90-degree movement from nose-up to ear-down and another back to nose-up. After each 90-degree turn the participant said "stop" when the perceived illusory motion disappeared. On the fourth set of head movements, the participant reported the direction and magnitude of the illusory motion. Motion sickness scores were reported throughout the experiment using a 0 to 20 scale where 0 represented "I am fine" and 20 represented vomiting. If the motion-sickness rating was below 3, the participant was asked to make a pitch forward head movement. Fifteen of the 20 participants performed pitch head movements, which are known to be very provocative. As before, when the perceived motion dissipated, the participant said, "stop" and immediately pitched the head back onto the bed. Afterward the participant reported the illusory tilt for both the forward and backward pitch head movements. Heart rate data was recorded throughout the experiment.

2.4.2 Adaptation study

This study determined the ability of humans to adapt, and retain adaptation to head movements made when moving the head out of the centrifuge's plane of rotation during short-radius centrifugation. Successful adaptation to AG will be necessary for the acceptance of intermittent short-radius AG as a practical space flight countermeasure. The primary hypothesis was that repeated exposure to a series of yaw head movements made during short-radius centrifugation in the light would result in a decrease of inappropriate VOR [6], illusory sensations, and reported motion sickness [7]. Light was thought necessary in order to enhance the sensory conflict between visual and vestibular stimulation, which in turn should drive the adaptation. The secondary hypothesis was that this adaptation was context-specific to the AG, and would be retained from one session to the next.



<u>Figure 2</u>: The eleven phases of the adaptation study.

Eight participants were exposed to three sessions of centrifugation, each lasting approximately 20 minutes. The sessions were performed on days 1, 2 and 8. Each session was divided into three phases: pre-adaptation, adaptation and post-adaptation. Participants made yaw head turns during all three phases of the experiment. Both pre- and post-adaptation phases were performed in darkness and involved participants making a set of four yaw head movements. One set of head movements consisted of a 90-degree turn from right-ear-down (RED) to nose-up (NU) in one second, followed by a 20-second pause and the return head movement from NU to RED. The adaptation phase lasted ten minutes and was performed in the light. The visual surround was the interior of the canopy, which rotated with the SRC. Participants were asked to make as many yaw head movements as possible in the same quadrant during adaptation in the light. Eye position data was recorded during all phases of the experiment. The Pensacola Diagnostic Index method [8] was used to assess the level of motion sickness after the experiment. Verbal reports of illusory sensations were reported during the fourth set of head movements made during the pre- and post-adaptation phases. Heart rate was recorded throughout the experiment. Figure 2 illustrates the experimental protocol of the adaptation study.

3. Results and Discussion

3.1 Illusory sensations

A simple model of semicircular canal function [9] predicts the following illusory sensations: For example, upon a counterclockwise yaw head-movement from RED to NU, the participant should feel a whole body pitch forward, and a clockwise rotation. Table 1 shows the percent of cases where participants reported illusory motion in the predicted and opposite directions. The majority of the 20 participants in the assessment study experienced the predicted pitch and roll, however a few participants perceived the illusory motion in the predicted plane, but in the opposite direction. This was the case in 13% of all reports. Those participants were inconsistent, that is, they did not always feel pitch and roll in the opposite direction.

Illusory tilt was not experienced uniformly. Upon yaw head turns about half the participants reported a simple pitch, usually of 30° or more. The other half reported a continuous pitch tumbling sensation of several revolutions. With respect to body roll, everybody experienced more than one complete revolution.

Subjective Motion	Predicted	Opposite	Corresponding To Actual Turn	None
Pitch	76 %	13%	-	11%
Roll	60%	13%	-	27%
Yaw	89%*	0%	11%	89%*

*Table 1: Percent of cases where participants reported illusory motion in the predicted direction for yaw head movements. *Note that pitch and roll body motion are predicted while yaw is not.*

We also found an interesting asymmetry between yaw head turns to NU and to ear-down (ED). The former produced significantly longer durations of illusory tilt. Presumably, the otoliths, which are differentially sensitive to head orientation with respect to earth gravity, are involved in modulating the strength and duration of this sensation.

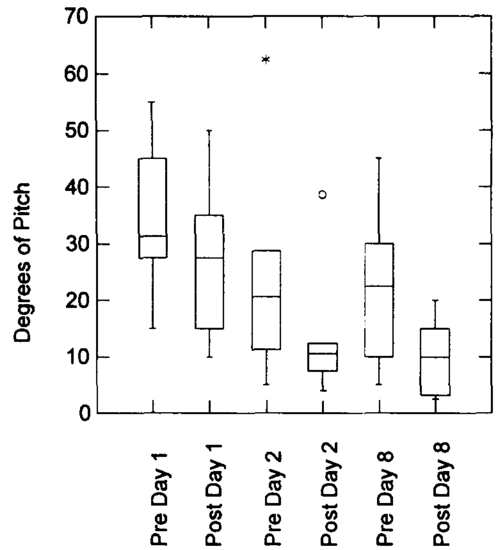


Figure 3: Reported pitch sensation experienced during pre- and post-adaptation head turns in the adaptation study, for 6 participants. One participant was unable to quantify the pitch sensation, and one outlier has been omitted from the box plot. The solid line marks the median of the sample and the height of each box shows the range of the central 50%. The box edges denote the first and third quartiles. The whiskers indicate the extent of the nearest points that are not considered outliers. The asterisk represents a mild outlier and the circle represents an extreme outlier.

Verbal reports of perceived pitch experienced during head turns in the adaptation study were obtained during the fourth set of yaw head movements made in the dark while rotating, during both pre- and post-adaptation phases. A main effect for pre- and post-adaptation head turns was found, indicating that the experienced pitch sensation decreased significantly between pre- and post-adaptation. A main effect was also found for day. The experienced pitch sensation decreased significantly between days 1 and 2. Retention of adaptation to day 8 was marginally significant. Figure 3 shows the reported pitch sensations during pre- and post-adaptation head turns for days 1, 2 and 8.

3.2 Motion Sickness

Inexperienced participants reported serious motion sickness during the assessment study. The experiment was aborted for 5 of the 20 participants. Yaw head turns were found to be less provocative than pitch head movements. However, large individual differences were discovered. On a scale from 0 (no symptoms) to 20 (about to vomit) about 30 % of the participants never exceeded a score of 3, while 15% reported ratings above 15 within a few minutes. Interestingly, susceptibility to motion sickness and perceived magnitude of the illusory tilt appear to be entirely unrelated.

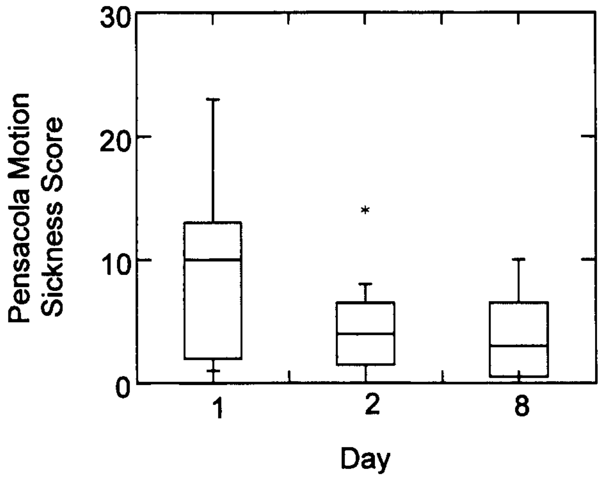


Figure 4: Pensacola Motion-Sickness Scores by Day for eight participants. The box plot shows that the median scores went down with repeated exposure. Also the variability between participants decreased as indicated by the shorter whiskers.

Pensacola motion-sickness scores were obtained immediately after centrifugation on each of the three test days during the adaptation study. Motion sickness was reduced with repeated exposure, and the decrease was retained over the following five days indicating retention of adaptation. This decrease was significant over all three days. Figure 4 shows the Pensacola motion-sickness scores by day for eight participants. (The maximum possible score is 51).

Repeated adaptation sessions administered to one of the authors showed that even after 12 consecutive days of centrifugation, inappropriate nystagmus and illusory tilt had not entirely disappeared. Illusory tilt continued to decline and motion-sickness ratings were approaching zero by day 4, despite the continued presence of the inappropriate non-compensatory eye reflex.

3.3 Heart Rate

Average heart rate was significantly elevated, from 70 beats per min (bpm) to 76 bpm, during the 23-second acceleration period in the assessment study. However, the gravitoinertial force gradient had no sustained effect on heart rate. No differences were found for our supine participants between the stationary phase before the bed started rotating, while rotating at constant angular velocity, or after the experiment had come to a stop. Each head turn during rotation produced a small but measurable increase in heart rate.

As shown in Figure 5, yaw head turns temporarily raised heart rate by about 5 bpm. Pitch head turns were significantly more provocative and raised heart rate by about 9 bpm.

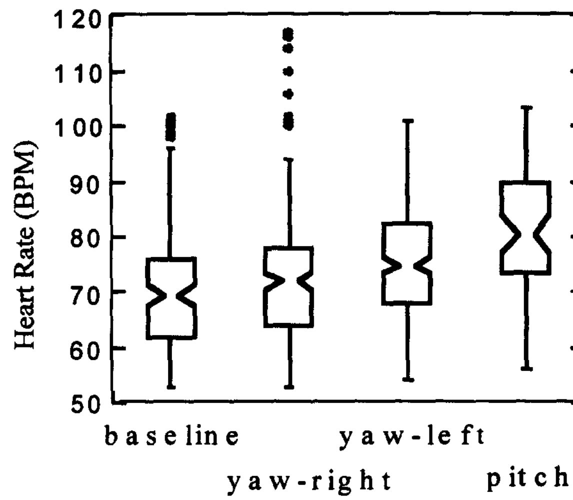


Figure 5: Distribution of heart rate for 20 participants. Median values and distributions are plotted as in Fig. 5. The notches point to the median, non-overlapping notch widths between head turns indicate significant differences. During baseline participants were supine and rotating at 23 rpm. Other conditions are associated with yaw or pitch head turns during bed rotation in the assessment study.

3.4 Vestibulo-ocular reflex (VOR)

Eye movements were recorded during all phases of the adaptation study. Slow phase eye velocity (SPV) was reconstructed from filtered eye movement data. Fast phases of the nystagmus were digitally identified and removed. The resulting slow phase velocity curve was then fit by a first-order decaying exponential. The magnitude A and the time constant τ were calculated from the curve fit, and R^2 values indicated the goodness of fit. A normalized SPV parameter was then calculated to measure VOR in the (inappropriate) vertical direction. This normalized SPV was determined by dividing the magnitude of the SPV response (A) by the stimulus. In this case, the angular acceleration stimulus creating the inappropriate vertical nystagmus was the change in the centrifuge angular velocity vector projection in the pitch plane of the head. Quantitatively it was the product of the sine of the magnitude of the yaw head movement times the angular velocity of the rotating environment (23 rpm, or 138 °/sec).

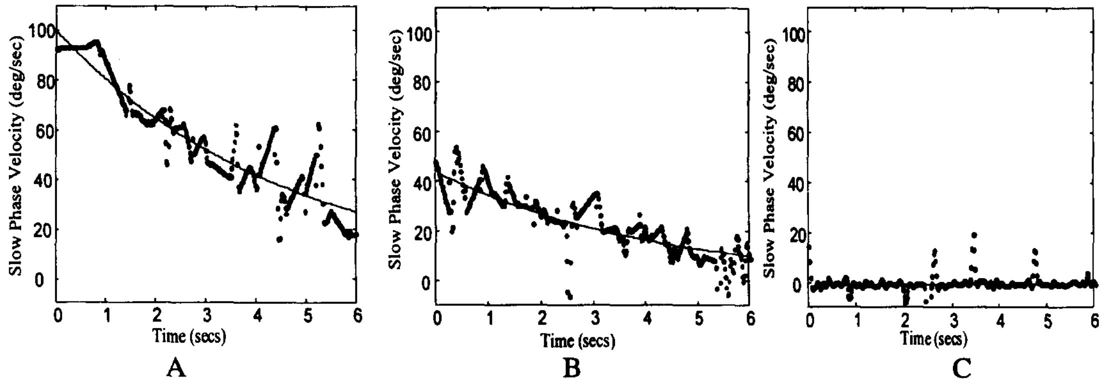


Figure 6: Raw slow-phase velocity profiles, in °/sec for one participant for head-turns from RED to NU (second repetition). Panel A: before adaptation on day 1 while rotating [R^2=.62, A=101.682 °/sec, τ=4.556 sec]. Panel B: after adaptation on day 8 while rotating [R^2=.34, A=41.939 °/sec, τ=4.015 sec]. The fast phases for panels A and B are in the upward direction. The equation for the curve fit is $Ae^{-t/\tau}$. Panel C: Before adaptation while making a head-turn on a stationary bed [R^2 not significant].

Figure 6 shows exemplar plots of the inappropriate vertical nystagmus. It is evident from the plots that the magnitude of these inappropriate vestibular reflexes decreases following adapting head movements in the light.

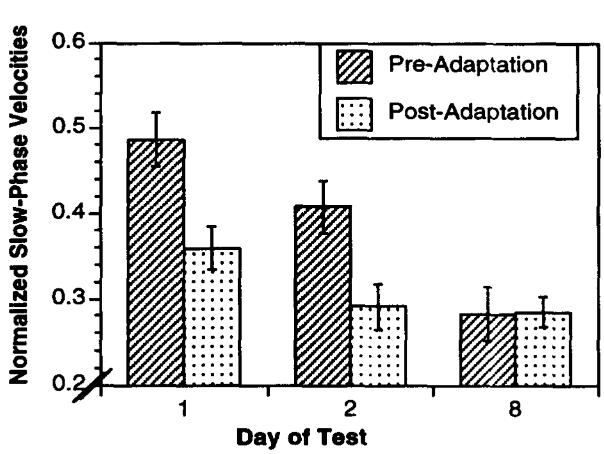


Figure 7: Normalized slow-phase velocities measured in the dark, before and after the 10-min adaptation period in the light. The values reflect averages of the second and third set of head movements for all 8 participants. Error bars indicate standard errors of the mean.

Figure 7 depicts the averaged normalized SPV values for eight participants based on the second and third head turns before and after adaptation. The normalized SPV differences were significant for the major effects of day, phase (pre-/post-adaptation), and phase*repetition (univariate repeated measures ANOVA analysis). The adapting head movements in the light were effective in reducing the vertical VOR measured in the dark. This adaptation effect was retained over five rest days. Eye movements were normal for head movements in the stationary environment, as illustrated in Figure 6 (Panel C).

4 Conclusion

The assessment study showed that all participants experienced an illusory tilt or tumble during head turns on the rotating centrifuge. However, individual differences appeared in the direction and magnitude of the illusory sensations. Even larger individual differences were found for motion sickness. Some participants appeared to be almost immune to Coriolis motion sickness, whereas others suffered from severe symptoms. A significant heart rate elevation was found to occur during acceleration up to 23 rpm, and a small but measurable increase was found during head turns.

The adaptation study showed that all measures (illusory tilt, post-experiment motion sickness, and the strength of the inappropriate vertical nystagmus) provide clear evidence of adaptation. This beneficial adaptation is maintained, to some extent, over a five-day rest period. The adaptation, however, was only partial. At the end of the second day, all measures had decreased by roughly one third of their initial magnitudes.

Conceivably, vestibular SRC stimulation during rapid head turns may be too strong to ever permit full adaptation at the high rotation rates required for g-levels equal to or greater than 1-g. Guedry [4] showed that humans can acquire direction-specific vestibular adaptation after 12 days of continuous 10-rpm rotation in the CCW direction. His participants had almost fully adapted and lost the typical sensations of tumbling and nausea. Unfortunately, this finding may not extend to higher angular velocities.

Assuming that the same mechanism that causes adaptation to centrifugation on Earth is also functional in microgravity, these results indicate that humans should be able to adapt to SRC countermeasures in weightlessness. In fact, the absence of any net gravitoinertial force acting on the otolith organs should, if anything, reduce the sensory-motor conflict associated with head movements during SRC AG [10]. Future studies need to address the acquisition, retention and generalization of this adaptation to different head movements and to different rotating environments. Astronauts may then be able to become pre-adapted to centrifugation before space flight. Pre-adaptation should also enable them to smoothly transition between rotating and non-rotating environments without any symptoms of illusory self-motion or motion sickness. The present results support the efficacy of short-radius centrifugation as a possible countermeasure to the debilitating effects of prolonged space travel. The conditions for complete adaptation as well as optimal adaptation schedules remain to be investigated.

4. Acknowledgements

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