ADAPTING TO ARTIFICIAL GRAVITY (AG) AT HIGH ROTATIONAL SPEEDS

Heiko Hecht, Erika L. Brown, Laurence R. Young

Man-Vehicle Lab, Massachusetts Institute of Technology
77 Mass. Ave., Bldg. 37-219, Cambridge, MA. E-mail: hecht@mit.edu

Hecht, H., Brown, E. L., and Young, L. R. Short-radius centrifugation offers a promising countermeasure to the adverse effects of prolonged weightlessness. Head movements made in a rotating environment elicit Coriolis effects, which seriously compromise sensory and motor processes. We have previously found that, contrary to common belief, participants can adapt to the Coriolis effects associated with single-quadrant yaw head turns during 23-rpm short-radius centrifugation, while maintaining their adaptation to stationary environments. Here, we focus on motion sickness and illusory motion, the most problematic subjective side effects. We present encouraging data that such context-specific adaptation generalizes immediately to a different centrifuge environment. It also generalizes quickly to Coriolis forces in the opposite direction. Implications for AG implementation are discussed.

INTRODUCTION

In the last forty years, the age of space travel has placed unique demands on the body, as every physiological system has been asked to deal with the novel weightless environment of orbit. In a manner of speaking, the body adapts too well to microgravity such that serious deficiencies emerge once the body is back in a 1-g environment, including a reduction in erythropoesis, a decrease in bone mineral density, disuse muscle atrophy, down-regulation of the baroreceptors, atrophy of the cardiac muscles, and desensitization of the vestibular system to tilt signals (Lathan & Clément, 1997; Young & Sinha, 1998).

Although the current era of low-earth-orbit flights places spacefarers within close reach of the medical resources of Earth, future flights will take us beyond the horizon of immediate help. The current countermeasures of exercise, lower-body negative pressure, fluid loading, and pharmacological measures addresses only the symptoms of adaptive decline, not the root of the problem itself. Furthermore, no combination of such countermeasures has proven adequate for long-duration space flight (Cavanagh, Davis & Miller, 1992; EDOMP, 1999; Goodship, et al, 1998; Nicogossian, Rummel, Leveton & Teeter, 1992). Artificial gravity (AG), on the other hand, uses the centripetal accelerations of a rotating environment to offer an integrated countermeasure that directly counters the problems of microgravity (Young, 1999).

Artificial Gravity

Stone's review (1973) of the human performance issues surrounding artificial gravity pointed to an ideal radius between 15.2 and 16.8 meters, with an angular velocity not to exceed about 6 rpm. Accordingly, research into the human tolerability of AG has been limited to studies with rotation rates below 10 rpm (Graybiel, 1973; Letko, 1973), and it has long been assumed that 4-6 rpm is the threshold for human comfort (Hall, 1997). Unfortunately, the construction and operation of vehicles that create AG with low rotation rates raises substantial economic and engineering barriers. Onboard short-radius centrifuges (SRCs) may offer a reasonable low-cost alternative; however, they have the serious disadvantage that high rotation rates are required to produce sufficient AG. We evaluate the benefits and problems of SRCs and summarize some promising experimental findings that suggest serious consideration of short-radius AG.

By providing intermittent AG to crewmembers aboard a standard spacecraft, SRCs would offer a low- cost countermeasure to microgravity deconditioning. A number of ground studies have provided evidence that short-radius centrifugation does indeed have the desired cardiovascular effects (Iwasaki, Sasaki, Hirayanagi & Yajima 2001; Burton & Meeker, 1992). Musculoskeletal atrophy may also be reduced by artificial gravity (D'Aunno, Thomason, & Booth, 1990) particularly if the static rotational stimulus is matched with dynamic loads of exercise (Gurovsky, et al, 1980).

Unfortunately, SRC has very unpleasant sensorimotor (e.g. Lackner and DiZio, 1998), vestibular, and perceptual side-effects (e. g. Hecht, Kavelaars, Cheung & Young, 2001). During head turns, the changes in angular velocity caused by bringing the semicircular canals into or out of the plane of rotation can cause disorientating sensations of illusory self-motion, improper reflexive eye movements, and motion sickness.

Pushing the envelope: Humans can adapt to rpm's between 20 and 30

The key concept determining whether in fact SRC is a viable alternative to large and expensive rotating habitats is that of context-specific adaptation (CSA). It is a defining characteristic of human sensory and motor systems that they habituate with repeated use. Muscles fatigue when repeatedly strained, a constant noise is soon filtered out, and with repeated head turns on a centrifuge, the experienced symptoms of motion sickness, and motion illusions become less severe. AG created by SRC, on the other hand, is limited to intermittent exposures and is only tolerable if two adaptive states (or even three: earth-g, 0-g, and AG) can be learned and preserved simultaneously. Young, Hecht, Lyne, Sienko, Cheung, and Kavelaars (2001) showed that such adaptation is in fact possible at 23 rpm. Inappropriate vertical nystagmus, illusory tilt and motion sickness adapt over multiple days without aftereffects.

In a more recent study (Brown, Hecht & Young,

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2002), we were concerned with the role of sensory conflict in driving this adaptation. We hypothesized that the stronger the opposition that the erroneous vestibular signal receives from the other modalities, the more thorough the adaptation. We tested three separate groups of subjects (Total N=19): one that was adapted in complete darkness (DARK), one that received a stable visual environment by means of a covered centrifuge with interior lighting (STABLE), and a third that was able to see the well-lit environment of the lab (EXTERNAL). While the visual feedback of retinal slip was necessary to adapt inappropriate eye movements, all three groups adapted equally well in terms of their motion sickness scores and the intensity of their experienced illusory body tilt. That is, some conflict that reveals the erroneous nature of the vestibular output is necessary for adaptation. However, the size of the conflict (whether vision was stable, a rotating field, or completely absent) did not matter. Figures 1 and 2 show the ratings for all groups across the three consecutive testing days for the respective measures. The number of head turns that subjects were willing to endure showed a significant daily increase [$F(2,54)=17.32$, $p<0.001$] which was consistent with the drop in motion sickness and illusory motion sensations.

From a practical perspective, motion sickness is perhaps the most important side-effect. We have tested several metrics for motion sickness and found that complex assessments do not add much, if anything, to a simple self-assessment by periodic prompting of the subjects for a rating between 0 and 20, where 0 represented "I feel fine" and 20 represented "I am about to vomit." We (Brown et al., 2002) showed a high correlation ($0.81< r <0.94$) between average and peak motion sickness ratings and assessment with a modified Pensacola scale (see Young et al., 2001; Hecht et al., 2001).

Does CSA generalize to different rotations and to different contexts?

One of the next pressing research issues was to assess whether CSA was limited to a particular Coriolis stimulus and to a particular centrifuge environment or whether the adaptation would generalize across stimuli and context. Only if that latter is true would a manageable pretraining on the ground be able to prepare astronauts for SRC in weightlessness. The experiment that follows shows evidence for both types of generalization.

Experimental Design. *Reversal*: we examined the specific nature of adaptation by covertly presenting 8 subjects with an unexpected change in rotational direction. They adapted to yaw head turns with a clockwise (CW) centrifuge rotation for three days. At the end of the fourth day, the direction was unnoticeably changed to counterclockwise (CCW), thus eliciting a novel vestibular stimulus. Three subjects remained for a fifth day with CCW rotation and were once again covertly presented with a novel (CW) stimulus.

Transfer: we investigated the nature of context-dependency of adaptation. A separate group of 6 subjects spent three days on-board the MIT short-radius centrifuge adapting to CW rotation. Days 4 and 5 also contained a reversal of centrifuge direction, but were carried out on-board the Brandeis rotating room, such that the subjects received identical vestibular stimulus with altered contextual cues.

In both experiments, steady-state rotation was at 23-rpm, such that the level of centrifugal acceleration at the subjects' feet was approximately equal to 1-g. The adaptive stimulus consisted of 15 minutes in a stable visual surround with right-quadrant 90°/sec yaw head turns made as frequently as the subject was comfortable making them. Test periods before and after this adaptation consisted of 6 yaw head turns performed in the dark at 30-sec intervals. Following the post-adaptation data collection period, the centrifuge was ramped down and immediately ramped back up to 138°/sec (see Figure 3); accelerations of 1.8°/sec^2 were used throughout.

Subjects. All study participants were healthy young adult volunteers recruited predominantly from the MIT community. Subjects were between the ages of 18 and 31. They were asked to abstain from consuming caffeine and

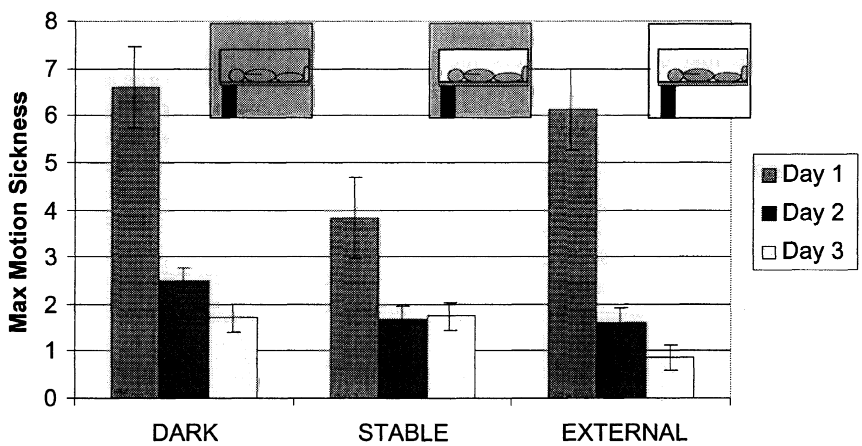

Figure 1: Maximum motion sickness scores (0-20) per day by experimental group.

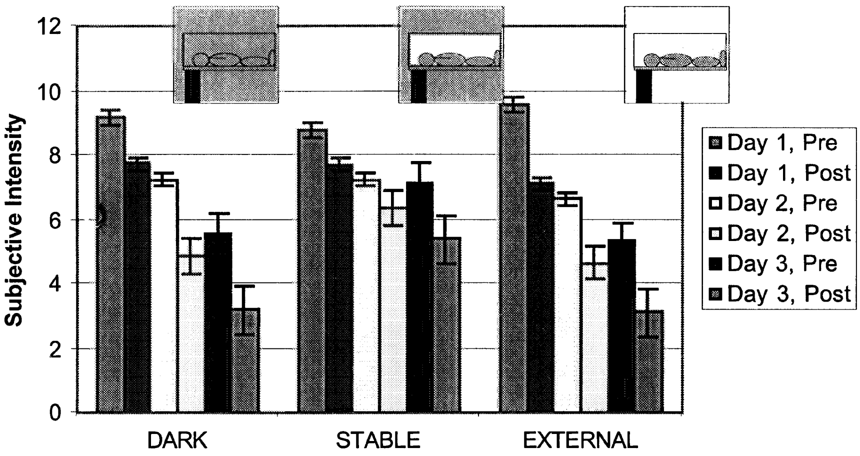

Figure 2: Ratings of subjective intensity of the illusory body tilt by (first head turn ever is anchored at 10) by day and by visual condition

alcohol from 24 hours preceding the start of the experiment.

Equipment. Data was collected before, during, and after the protocol each day to test the levels of adaptation, as measured by changes in motion sickness scores, inappropriate vertical nystagmus, and magnitude and duration of illusory tilt. MIT's 2-meter radius Short Radius Centrifuge (SRC) provided the primary rotating platform for this experiment. This 1-Hp "rotating bed" supports the subject supinely with the crown of the head on-axis, while an adjustable foot plate provides support in the radial direction (for details see Young et al. 2001; Hecht et al. 2001). An opaque cover was utilized to block visual cues from the surrounding. Three on-board lights provided a fixed visual frame of reference and a digital video camera with infrared capabilities allowed constant monitoring. The Brandeis Rotating Room provided the same Coriolis stimulus although it was a large round room (3.35 m radius) with no view of the outside world. A stable visual frame of reference was provided by on-board fluorescent lighting, and an infrared video camera once again provided monitoring capabilities for the two experimenters outside the room. The subject was placed supine, head at center, feet pointing outward.

Results

Motion sickness behaved practically identical to the values shown in Figure 2: starting on day 3 the ratings did not exceed 1. The reversal of rotation direction had no significant effect. Neither did the context change to the Brandeis centrifuge. That is, the adaptation of motion sickness had generalized.

As a second measure, the modified Pensacola motion sickness scale mentioned above was used as a diagnostic immediately following each day's rotation. This scale quantified the severity of individual motion sickness symptoms (headache, nausea, pallor, etc.) to provide a detailed snapshot of the peak nausea experienced by a subject on a given day. No context or direction reversal effects were found.

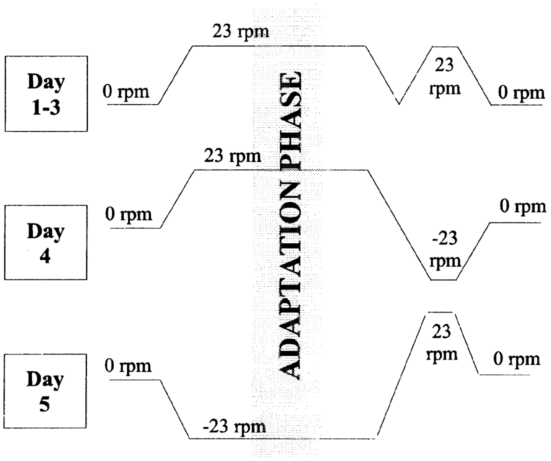

Figure 3: Velocity profiles for centrifuge protocols

Illusory tilt: During the head turns made while the centrifuge was rotating, subjects experienced illusory feelings of tumbling or tilt as their equilibrated semicircular canals were brought into or out of the plane of rotation (for a model regarding the quality and cause of these tilt illusions see Hecht et al. 2001). Intensity ratings and duration of this illusory tilt were used as measures of the subjective experience. We utilized a rating scale anchored at "10" representing the intensity experienced for the first head turn made during rotation on the first day. As shown in Figure 4, intensity ratings went down from the pretest in the dark over the light adaptation phase, followed by the first post-tests in

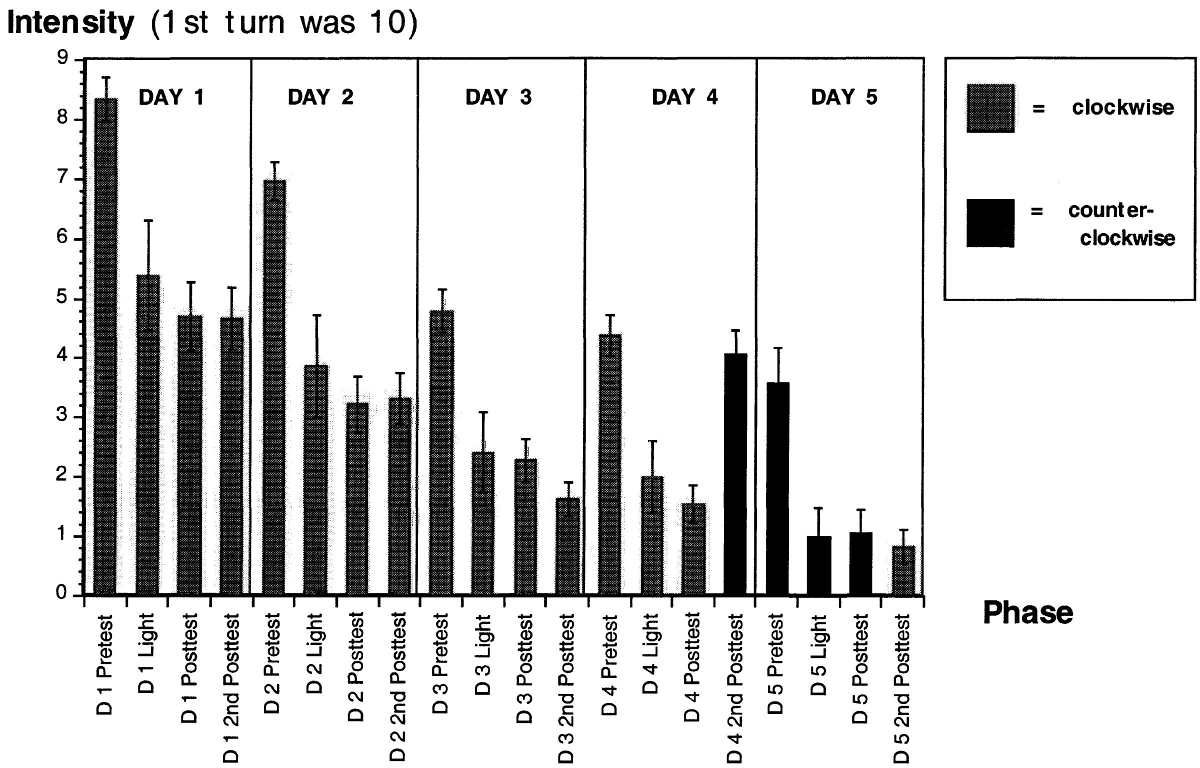

Figure 4: Stimulus change: average intensity ratings obtained on MIT centrifuge on 5 consecutive days of making head-turns in right quadrant. Note that the direction of the centrifuge was reversed at the end of days 4 and 5. Error bars indicate standard errors of the mean.

the dark. On each day the centrifuge was then ramped down and spun up again for a second post-test. On day 4 the centrifuge's direction of rotation was reversed for the second post-test. Not only did intensity ratings become smaller within each day [$F(3,18)=18.17$, $p<0.001$] they also adapted across day [$F(3,18)=19.55$, $p<0.001$]. The post-test after direction reversal was significantly higher then the preceding post-test [$F(9,54)=4.93$, $p<0.001$], but it was not higher than the pretest on that day 4. Only three subjects were able to return for a fifth day, however, it is clearly visible that they had become thoroughly adapted to both rotation directions of the centrifuge.

The other group that followed the identical protocol but was moved to the Brandeis rotating room for days 4 and 5 showed identical results. That is, the location change neither erased nor compromised the adaptation.

Discussion

Adaptation occurs consistently. Four daily training sessions of approximately 1 hour at 23 rpm are sufficient to reduce motion sickness and illusory tilt sensations to very tolerable levels. This adaptation was context specific in the sense that it did not produce any aftereffects when back in the non-rotating environment.

Changing the centrifuge's direction while making the same head turns produces an opposite vestibular signal. While this reversal could have been potentially very upsetting, the illusory tilt that it produced was comparatively small and very transient. When asked to tell us why they gave a higher intensity rating at the end of day 4, with the exception of one subject no one guessed that we had changed the direction of rotation.

Adaptation on day 4 did not change significantly based on experiment location and hardware. The adaptation acquired in one locale (MIT rotating bed) transferred completely to a very different environment (Brandeis rotating room). This result could not have been more positive with respect to pre-adapting astronauts on ground based centrifuges that look and feel very different than what will have to be implemented in a spacecraft.

Graybiel (1977) found short term loss of adaptation when changing the direction of rotation for slow rotational speeds (6 rpm). We have demonstrated that adaptation to rotation in one direction at a much higher rotation rate conferred some generalized immunity as well as the ability to rapidly adapt to same-quadrant yaw head turns made during rotation in the opposite direction.

The feed-forward stimulus of location (and the specific smells, sounds, and feels that go with it) do not seem to provide a necessary condition for assuming the adaptive state. More likely feeling the fluid shift or noticing vestibular conflict itself put the subject in the adequate CSA.

If, as has been suggested by previous flight research (Graybiel, Miller, & Homick, 1977), microgravity actually provides an even less nauseating environment for centrifugation, then vestibular problems should certainly no longer remain an excuse that stands in the way of flight-testing an SRC countermeasure. An orbiting test platform would allow not only definitive answers to the interaction of otoliths and canals in the process of vestibular adaptation, but would also provide the first solid data beyond bed rest analogues about the efficiency of AG against musculoskeletal and cardiovascular losses. Furthermore, only in microgravity does the opportunity arise to examine the physiological effects of partial-g loads, those between microgravity and Earth-normal 1-g.

In order to truly address the operational aspects of short-radius AG, a centrifuge must be made available on orbit. It is time to start truly answering the questions of "how long", "how strong", "how often", and "under what limitations" intermittent artificial gravity can be provided by a short-radius device.

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