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Artificial gravity—head movements during short-radius centrifugation: Influence of cognitive effects

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Abstract

Short-radius centrifugation is a potential countermeasure against the effects of prolonged weightlessness. Head movements in a rotating environment, however, induce serious side effects: inappropriate vestibular ocular reflexes (VOR), body-tilt illusions and motion sickness induced by cross-coupled accelerations on a rotating platform. These are well predicted by a semicircular canal model. The present study investigates cognitive effects on the inappropriate VOR and the illusory sensations experienced by subjects rotating on a short-radius centrifuge (SRC). Subjects ($N = 19$) were placed supine on a rotating horizontal bed with their head at the center of rotation. To investigate the extent to which they could control their sensations voluntarily, subjects were asked alternatively to "fight" (i.e. to try to resist and suppress) those sensations, or to "go" with (i.e. try to enhance or, at least, acquiesce in) them. The only significant effect on the VOR of this cognitive intervention was to diminish the time constant characterizing the decay of the nystagmus in subjects who had performed the "go" (rather than the "fight") trials. However, illusory sensations, as measured by reported subjective intensities, were significantly less intense during the "fight" than during the "go" trials. These measurements also verified an asymmetry in illusory sensation known from earlier experiments: the illusory sensations are greater when the head is rotated from right ear down (RED) to nose up (NU) posture than from NU to RED. The subjects habituated, modestly, to the rotation between their first and second sequences of trials, but showed no better (or worse) suppression of illusory sensations thereafter. No significant difference in habituation was observed between the "fight" and "go" trials.

1. Introduction

Traditional countermeasures against the effects of prolonged weightlessness, such as exercise, resistive garments or lower-body negative pressure devices appear to be insufficient or onerous in practice. Because it attempts to remove the cause of these effects rather than alleviating their symptoms, artificial gravity (AG) represents a promising countermeasure against cardiovascular deconditioning, bone and muscle loss and neurovestibular disturbances. Any AG centrifuge device must meet low cost and adaptability to the existing spacecraft, and must thus be of limited

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radius (on the order of 2–3 m). The corresponding angular velocity required to create a 1 g force at the rim of the centrifuge is up to 30 rpm. At these high velocities, any head movement bringing the semicircular canals out of the plane of rotation creates unexpected illusory sensation, inappropriate vestibular ocular reflexes (VOR) and motion sickness. Therefore, the key to the practical use of short-radius AG as a countermeasure to the effects of 0 g is to allow the crew to enter and exit the SRC regularly without suffering renewed space motion sickness. It is thus necessary to determine whether adaptation can be achieved and maintained, to investigate the specific mechanisms that drive adaptation, and to set up an optimized schedule that will achieve and maintain adaptation as efficiently as possible. A number of variables such as the type and velocity of the head movements or the length of the rest periods can be manipulated to facilitate the adaptation.

Young et al. [1] and Hecht et al. [2] have investigated the effects of yaw head movements during rotation and have shown an adaptation of the anterior semicircular canal driven by the exposure to movement in the light. This study deals with the optimization of the adaptation process and emphasizes factors that are related to the subject's mental set during adaptation. Literature suggests a cognitive control of the vestibular ocular reflex: Barr, Schultheis and Robinson [3] proved that it was possible to achieve voluntary nonvisual control of the human VOR: subjects that were rotated on a rotation chair at 0.3 Hz in darkness showed respective gains of 0.65, 0.95 and 0.35 when asked to perform mental arithmetic tasks, to fixate an imaginary target, and to imagine a target rotating with them. Berthoz and Melvill-Jones [4] discussed the importance of cognitive factors in VOR adaptation. Therefore, if cognitive effects are generally as strong as suggested it might be possible to capitalize on this to optimize the adaptation process, since conflicting vestibular stimulation is not only nauseating but also disturbing from a cognitive point of view. The first step is then to determine whether mere instructions suffice to significantly alter the VOR and the illusory sensations, and to determine if such instructions facilitate or interfere with the context-specific adaptation.

2. Experimental methods

2.1. MIT short-radius centrifuge

The MIT short-radius centrifuge (SRC) has a 2 m radius and rotates a supine subject clockwise about an axis that is perpendicular to the body and passes just above the head. The centrifuge is driven by a one-hp electric motor through a 50:1 gear reduction. A 300 MHz PC running Labview software (version 5.1) generated velocity profiles and controlled the velocity of the centrifuge. A Hewlett-Packard optical encoder (256 CPR) mounted to the centrifuge provided accurate velocity readings. The centrifuge was operated at 23 rpm, creating a 1 g force at the feet of a 168 cm tall subject. A 32-channel slip ring located at the center of the support structure was used to transmit data from the centrifuge to the data acquisition system. An on-board RCA infrared color video camera was mounted to one end of the centrifuge and wired through the slip ring to provide real-time images of the subject during centrifugation, even in the dark.

2.2. ISCAN raw eye movement data acquisition software

An ISCAN raw eye-imaging system measured the displacement of the corneal reflex and pupil and allowed us to assess the reflexive eye movements resulting from the head movements during centrifugation. Eye position was sampled at 60 Hz and displacements were measured to a precision of $\pm 0.3^\circ$ over a range of roughly 20° in the horizontal and vertical directions. The ISCAN eye imaging goggles were powered by two on-board 12 V batteries and wired through the slip ring. A 300 MHz PC collected the ISCAN data, and two monitors were used to help the operator control the experiment.

2.3. Additional equipment

The subject pressed a duration/sensation button to specify the point in time on the corresponding nystagmus plot at which the sensations occurred. A simple on/off button was connected to a 9 V battery, and the analog voltage signal was recorded by ISCAN software. All subjects were instructed to press the button when they initiated a head movement and to release it when the illusory motion sensation disappeared. To control the trajectory and the absolute angle of each head turn, the subject positioned his/her head in an adjustable helmet connected to a head restraint. This device consisted of an aluminum plate which allowed yaw head movements only, a potentiometer measuring the head position, and two adjustable metal stops limiting the amplitude of the head movements. The ISCAN software recorded the analog voltage of the potentiometer. In order to prevent any light cues during the experiment, a windshield canopy that covered the entire length of the centrifuge was darkened with a black cloth, and the goggles were covered with a blindfold.

2.4. Subjects

There were 19 subjects (12 males, 7 females) who took part in this experiment. They were selected largely from the MIT student population and their age ranged from 17 to 59 years. Prior to centrifugation, all subjects were familiarized with the experimental protocol and procedures. They were advised that they could possibly experience symptoms of motion sickness, and that they would be free to terminate the experiment at any time. The subjects were instructed to abstain from caffeine for the 24 hours preceding the experiment and asked to perform the experiment without glasses or contact lenses to prevent secondary reflections. On the day of the experiment, each subject was asked to provide demographic data (age, gender, race, hand and eye dominance, centrifugation experience), and to estimate their general level of health. The height and weight of each subject was recorded to enable proper position of counterbalancing weights on the centrifuge. Blood pressure and heart rate were measured both in standing and supine position and a Romberg test ruling out any vestibular defects was administered. Any abnormality in these measures resulted in an exclusion of the subject from the study. The MIT Committee on the Use of Humans as Experimental Subjects (COUHES) approved the experimental protocol for this experiment.

2.5. Design and procedure

This study investigated the intensity of illusory sensations, motion sickness, and inappropriate VOR resulting from yaw head turns during clockwise short-radius centrifugation. To a centrifugation session lasting between 30 and 40 min 19 subjects were exposed.

Subjects were positioned on the centrifuge in a supine body position with their head in the helmet located on the bed's vertical axis of rotation. The height of the helmet was adjusted until no slip was observed between the head and the helmet when performing a head movement. The safety belt was then fastened and the foot plane adjusted until it was in contact with the soles of the subject's feet analogous to that felt when standing up. Subjects performed practice head movements until they naturally made one head movement in approximately one second irrespective of their posture and until they could maintain the amplitude of their movements nearly constantly: the absolute angle of head yaw turn that each subject could comfortably reach was then noted to within the nearest 10° increment and a metal stop was placed in the restraint at this location, defined as the right ear down (RED) position. A second metal stop was placed at a value of 0 defining the nose up (NU) position. The eye movements were then calibrated via a removable stand, which consisted of a cross suspended 71 cm above the subject's head, showing five separate dots, one of which was centered directly above the midpoint between the subject's eyes. Calibration was completed using ISCAN's raw eye movement data acquisition software.

To eliminate visual cues, the light was switched off and subjects were asked to adjust a blindfold until they reported complete darkness. The centrifuge was then rotated in a clockwise direction at a constant acceleration of $6^\circ/s^2$ until an angular velocity of 23 rpm ($138^\circ/s$) was achieved.

The experiment consisted of 6 distinct phases, all conducted in the dark: during each phase, eye movements were recorded while subjects performed three directed sets of head movements, each set consisting of a yaw head turn from RED to NU followed by a 20 s pause and the return head movement from NU to RED. Each head movement was initiated by a countdown performed by the operator. Almost all subjects experienced illusory pitch and roll sensations when they performed these yaw head turns during centrifugation.

Phase 1 established a baseline level for the measurements. During phases 2 and 3, subjects were asked to deal with their illusory sensations in one of two ways: They were instructed either to "fight", try to resist mentally and suppress any sensations of motion beyond that of the yaw head movement they were actually performing, or to "go", acquiesce in, concentrate on and enhance the illusory tilts they experienced when making a head movement by imagining themselves tilting in the same direction. Prior to the experiment, the subjects were explained what type of illusory motion they could possibly experience when the yaw head turns are performed during centrifugation. There were two, non-overlapping groups of 8 subjects each. Group "go-first" received "go" instructions for phases 2 and 4, and "fight" instructions for phases 3 and 5. The other group, "fight-first" had "fight" instructions for phases 2 and 4, and "go" instructions for phases 3 and 5. Phase 6 measured post-experimental baseline quantities.

2.6. Subjective measures

During the session on the centrifuge, subjects were asked to report their level of discomfort (motion sickness), the intensity of the illusory sensations, and the ability to follow the "go" and "fight" instructions to mentally influence the illusory sensations (estimation of the success score).

2.7. Motion sickness

Subjects estimated their level of discomfort on a scale from 0 (perfectly comfortable) to 20 (frank vomiting). If at any point during the experiment a subject reported a rating of 15 or above, they were given a rest while continuing to rotate, until their rating fell below 15. The operator, after consulting the subject, would then decide to pursue or abort the experiment.

2.8. Intensity ratings

A scale provided milestones to help subjects describe their illusory sensations. The sensation felt with the first head movement of phase 1 (neither "fight" nor "go") made in the rotating environment was assigned an arbitrary intensity of 10 and later sensations were reported relative to that score. For example, a head turn that the subject experienced twice as intense as the first one was then rated with an intensity of 20; accordingly, if a head turn was experienced half as intense as the first one the subjects rated an intensity of 5. Finally, if the head turn felt identical to a turn made in a stationary environment (centrifuge not rotating), the subjects rated an intensity of 0.

2.9. Success scores

After each head movement in phases 2–5, subjects were asked to estimate their success in following the operator's specific instruction of "go" or "fight", using a scale from 0 ("I did not succeed at all") to 10 ("I have succeeded perfectly"). They were also asked to report the direction of their illusory tilts during the third set of head movements of each of these phases.

3. Analysis techniques

3.1. Subjective measures

After each head turn in test phases 2–5, subjects estimated their subjective intensities, motion sickness and success scores, using the scales described above. There were 6 head movements by phase, resulting in 52 data points per subject (24 points of subjective intensities, 4 points of motion sickness and 24 points of success scores).

3.2. Eye data

The eye data were processed using a MATLAB code reconstructing the eye velocity from the filtered eye movement data recorded by the ISCAN software [1]. Fast phases of the nystagmus were digitally identified and removed from the velocity profiles, and the resulting residual slow phase velocity (SPV) curve was fit by a first-order exponential $\mathrm{SPV} = \pm A e^{-t/\tau}$ for each half, respectively.

The MATLAB code calculated the magnitude A and the time constant τ characterizing the decay of the SPV, as well as an F-parameter value measuring the reliability of the fit. A manual fit was made instead whenever one of the three following conditions was met:

(a) A time interval of the nystagmus curve was skipped by the code because of noise or missing data,

(b) The F-parameter had a value less than 3, indicating a non-significant fit,

(c) An amplitude (or time constant) fell beyond the expected limits [0; 150] (or [0; 20]).

To regularize statistical comparisons between subjects, the magnitude of the slow phase velocities (A) were normalized within subjects by the sine of that subject's head-turn angle (i.e., that subject's stimulus) and overall to the bed rotation velocity 138 deg/s. The final normalized slow phase velocity (NSPV) was computed according to

$$\mathrm{NSPV} = \frac{A}{\sin\left(\mathrm{HeadAngle}\frac{\pi}{180}\right)138}.$$

When the head was placed at the centre, the normalized slow phase velocity was computed using the subject's position of the RED on the head restraint. If this information was not available, it was computed using the head position recorded by the on-board potentiometer. Finally, in cases of equipment failure, the normalized slow phase velocity was calculated using the averaged RED position obtained from all the other subjects. The averaged head turn angle was 72.5° (S.E.: 2.2).

Eye data information was processed for the initial baseline phase and for the four "go" and "fight" phases, resulting in 60 measures per subject (30 data points for the normalized slow phase velocity, and 30 data points for the time constants) from 3 repetitions ×2 postures (from RED to NU and from NU to RED) per phase. Only the data for the "go" and "fight" phases were processed, and comparisons with the data from the baseline phase were performed in case it was relevant.

3.3. *Weighting the data by the subjective report of success of "fight" and "go" efforts*

The success scores (1–10) reported by the subjects were used to estimate an error in each measure. It was assumed that a reported value of five characterized subjects that were uncertain as to success or failure of their performance, and that values of 0 or 10 indicated certainty of failure or success, as the case may be.

$$\varepsilon^2 = \frac{1}{1 + (5 - \mathrm{SuccessScore})^2}$$

The first analysis used SYSTAT (version 1.0) to perform a General Linear Model Repeated Measures ANOVA on the 4 subjects who had a complete set of data. The results did not show any significant effect of phase for the same condition (e.g., "fight-first"). Data points (i.e. normalized slow phase velocity, time constants, subjective intensity and motion sickness scores) corresponding to the same head turn in phases of identical condition were then averaged, measure-by-measure, and each point was weighted by its error, ε^2, when that average was computed. This gave greater weight to the more reliable measures (as the subject reported them).

4. Results

4.1. *Normalized slow-phase velocity*

There was no significant VOR difference between the "fight-first" and the "go-first" groups ($F = 0.364$, $p = 0.573$), nor the "fight–go" treatment ($F = 0.011$, $p = 0.922$), nor the posture ($F = 1.761$, $p = 0.242$), and no effect of habituation across repetitions ($F = 1.151$, $p = 0.355$) was found. The average normalized slow-phase velocity for turns in the "go" phase (0.383) was virtually identical to the average in the "fight" phase (0.382) and both values were not significantly different from average in the initial baseline phase (0.366). No significant difference was found between the "go" and "fight" phases by posture ($F = 0.749$, $p = 0.426$) or across repetitions ($F = 1.455$, $p = 0.279$).

The analysis revealed a nearly significant triple cross effect ($F = 5.967$, $p = 0.058$), gender × posture × condition. This effect, however, appeared to be unreliable. When the analysis was repeated 8 times, once each with each of the 8 subjects omitted, the effect was not significant in 3 of those 8 analyses.

4.2. *Time rates of slow-phase velocity decay*

When the time constants of the same 8 subjects were analyzed by the same software module, no significant effect of the "fight–go" treatment ($F = 0.390$, $p = 0.560$), of the posture ($F = 2.199$, $p = 0.198$), and no effect of habituation across repetitions ($F = 0.970$, $p = 0.412$) was found.

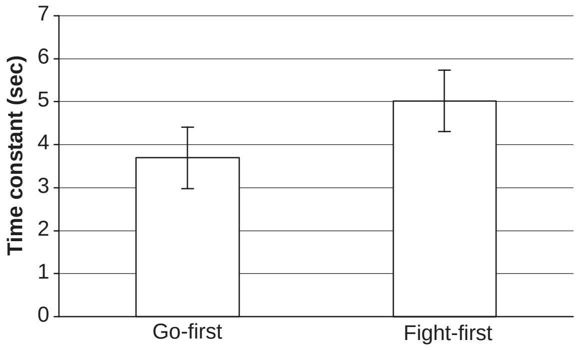

Fig. 1. Time constants of the SPV decay for the "go-first" and "fight-first" groups.

However, there was a significant effect ($F = 11.241$, $p = 0.020$) of the "fight-first" condition. Subjects from this group had a time constant of 5.017 (S.E.: 0.717), which was equivalent to the one measured in the initial baseline phase, 5.053. Data from the "go-first" group showed that performing "go" head turns at the beginning of the session (rather than the middle) resulted in a significant shorter time constant of 3.693 (S.E.: 0.717). The VOR decayed significantly faster for this group (see Fig. 1).

4.3. Motion sickness

A significant effect of the "fight–go" condition on the motion sickness scores was found by the same analysis, performed on 16 subjects ($F = 5.494$, $p = 0.036$). The average motion sickness scores for the "fight" phases was 1.5 and it was 1.1 for the "go" phases. However, it was not persuasive due to the low levels of motion sickness generated by the experiment: most subjects (10 out of the 16 analyzed) did not show any discomfort when they executed head movements during centrifugation. Six out of the 16 reported a slight discomfort that varied across subjects but did not vary within subject by the instructions ("fight" or "go").

4.4. Subjective intensities

Subjective intensities of illusory sensations while making head turns on the centrifuge were analyzed for 16 subjects, 8 starting with "go" trials and 8 starting with "fight" trials (see Fig. 2). Three subjects were removed from the analysis because of incomplete data. The same analysis as before did not find any significant effect of "fight-first" ($F = 1.547$, $p = 0.236$), but it found the intensities for "go" head turns to be significantly larger, 9. 250 (S.E.: 1.092) than for "fight" head turns, 6.915 (S.E.: 1.092), $F = 18.231$, $p = 0.001$ (see Fig. 2).

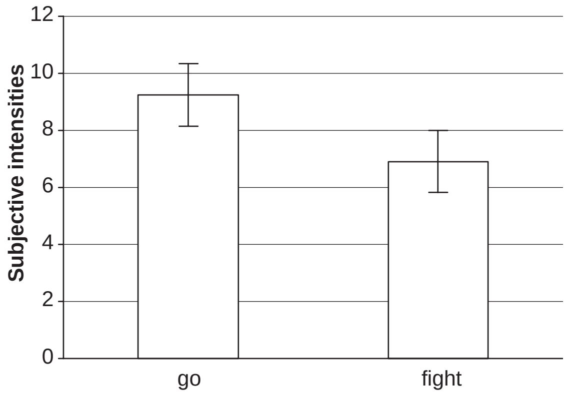

Fig. 2. Subjective intensities of the motion sensation during short-radius centrifugation.

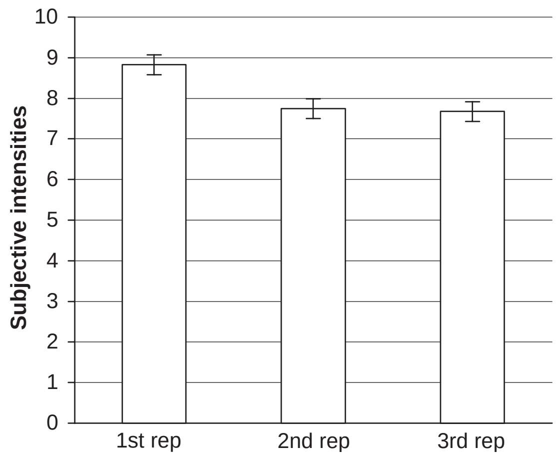

Fig. 3. Subjective intensity as a function of repetition.

As Fig. 3 indicates, there was a significant habituation seen across repetitions, $F = 17.848$, $p = 0.0005$. The subjective intensities were larger for the first repetition, and smaller (but roughly equal) for the later repetitions. This habituation pattern was substantially the same for the "go" and "fight" conditions.

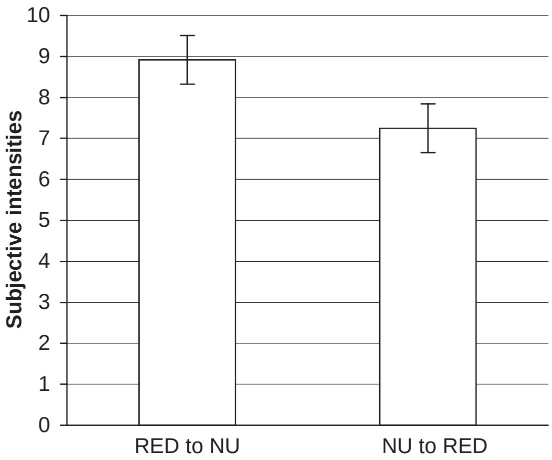

Fig. 4. Subjective intensities for the two different head stop positions, NU (left side) and RED (right side).

Finally, the average subjective intensity for head turns from RED to NU was larger than from NU to RED, $F = 27.533$, $p = 0.0005$ (see Fig. 4), as is consistent with previous findings [5].

5. Conclusion

Short-radius centrifugation is practical as a generalized countermeasure to the effects of weightlessness if adaptation to high-speed rotations can be made practical and convenient. Optimizing ground pre-adaptation to centrifugation is an important element in its use. This study found that centrifugation sessions were significantly easier to tolerate if subjects were asked to anticipate the expected illusions and to “fight” them. By contrast, the only significant effect of the “fight” or “go” conditions on the VOR was a reduction in the time rate of SPV decay that could be achieved by having the “go” trials at the beginning (rather than the middle) of the session. However, those trials in which the “go” phase came first also produced more intense illusory sensations. As a compromise, therefore, it may be worth experiencing intense illusory sensations in the early moments of the centrifugation to minimize the global length of the inappropriate VOR over the session, even in the dark. Or, it might be more efficient to begin with “fight” trials and thus minimizing the overall average intensity of the illusory sensations, and accept the greater length of SPV decay in return. Based on our previous research, there is evidence that eye movements and subjective estimates can partly dissociate during short-radius centrifugation [1,2].

In this study, we have decided to test the same subjects with both types of instructions rather than testing two separate groups of subjects with either the “fight” or the “go” condition. This has the advantage that we were able to demonstrate that merely changing the instruction (“fight” or “go”) influences how subjects perceive the illusory sensations during short-radius centrifugation. Rather large individual differences also spoke for this design. We also observed an effect of order. It is not known, for the moment, if the greater brevity and efficiency of VOR that early “go” trials generated can be maintained over days without refresher training. Some knowledge of the requirements for such adaptation would be helpful in order to estimate the price in discomfort needed to reduce the duration of the vestibular nystagmus. On the basis of this experiment it would be premature to recommend any particular cognitive strategy such as “fight” or “go”. However, we think it is worthwhile pursuing the investigation of cognitive factors further because this research will help to better understand the mechanisms that underlie illusory motion sensations during short radius centrifugation.

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