Eur J Appl Physiol (2001) 85: 539–545
DOI 10.1007/s004210100494

ORIGINAL ARTICLE

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Effects of cosmonaut vestibular training on vestibular function prior to spaceflight

Accepted: 7 June 2001 / Published online: 9 August 2001

Abstract The purpose of this study was to quantify the effects of repetitive Coriolis and cross-coupled stimulations, similar to the vestibular training the cosmonauts are exposed to prior to their spaceflight, on vestibular function in control subjects on Earth. Ten volunteers were passively rotated in yaw on a rotating chair while executing standardized pitch head-and-trunk movements. The chair stopped to change direction after 12 head-and-trunk movements were made. The runs were grouped in sessions of ten,which were repeated daily for 10 days. The severity of motion sickness was assessed by subjective judgment and measurements of skin pallor and salivary total protein concentration, and nystagmus was recorded. The severity of motion sickness and nystagmus decreased during cosmonaut vestibular training (CVT). One month after the end of CVT, nystagmus responses were still about 20–30% lower than control values. These results indicate that CVT induces a habituation of vestibular responses. One important implication of this experiment concerns space studies on cosmonauts who are exposed to such vestibular training prior to their spaceflight.

Keywords Cosmonauts · Vestibular training · Motion sickness · Nystagmus · Habituation

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Introduction

When a rotating individual makes a head movement out of the axis of rotation, his or her semicircular canals undergo cross-coupled angular accelerations and his or her otolith organs are exposed to a linear Coriolis acceleration. Such stimulation elicits disorientation (often referred to in aviation as the "Coriolis effect"), nystagmus, and motion sickness symptoms (Graybiel et al. 1977; Lackner and Graybiel 1986; Bles 1998).

Since the first manned space missions, Russian cosmonauts have been exposed to a ground-based adaptation program, or cosmonaut vestibular training (CVT), which includes Coriolis and cross-coupled angular accelerations, in an attempt to minimize the occurrence of space motion sickness (Gurovskiy 1966; Popov et al. 1970). During CVT, cosmonauts in a rotating chair execute pitch head movements until either vomiting is effected or a predetermined number of head movements is performed. This training is achieved through daily sessions of repeated exposure to body yaw rotation with chair acceleration and deceleration of $180°/s^2$. The number of sessions ranges from 4 to more than 12, depending on the initial susceptibility of cosmonauts to Coriolis-induced sickness. CVT generally takes place during the final 2 weeks before launch (Krioutchkov et al. 1993).

During initial exposure to weightlessness, head movements, especially in pitch, tend to elicit space motion sickness (Graybiel 1980; Matsnev et al. 1983). This may indicate that the lack of confirming otolith cues during head pitch is particularly provocative (Oman et al. 1986). The rationale behind CVT is that tolerance to the conflict between the semicircular canals and nonconforming otolith cues generated by Coriolis and cross-coupled angular accelerations on Earth would transfer to weightlessness conditions (Popov et al. 1970). Although there is no clear evidence of the effectiveness of CVT on space motion sickness, the incidence of space motion sickness in the Russian space program is generally claimed to be lower than that of the US space program (Davis et al. 1988).

There is some indication that on Earth the repeated exposure to passive body rotation elicits a gradual decrease in vestibular responses, a phenomenon known as vestibular habituation (Collins 1973). During CVT, the pattern of repetitive angular velocity steps during chair starts and stops might also be responsible for the habituation of vestibular responses in cosmonauts before they go to space. One important implication of CVT concerns the use of "habituated" cosmonauts as subjects for adaptive studies of vestibular functions (i.e., perceptual, vestibulo-ocular, or postural responses) to weightlessness. Markedly lower vestibulo-ocular and perceptual responses in cosmonauts compared to control subjects have been attributed to the potential effect of CVT (Clarke et al. 1993; Wetzig et al. 1993). Therefore, it is of interest for the space vestibular research community to know the actual effects of CVT. Previous studies have described a reduction in illusory motion, nystagmus, and nausea during continuous exposure to Coriolis and cross-coupled vestibular stimulation (Guedry 1965). The aim of the present experiment was to characterize the changes in the severity of Coriolis-induced sickness and in the vestibulo-ocular responses when subjects are exposed to the same vestibular training as cosmonauts prior to their spaceflight.

Methods

Subjects and equipment

The experiment was carried out in the Space Flight Medicine Clinic of MEDES in Toulouse, France. The experiment was approved by the Comité Consultatif de Protection des Personnes dans la Recherche Biomédicale of the Midi-Pyrénées region of France. The subjects signed a consent form that was approved by this committee. The subjects were four men and six women aged 23–31 years [mean (SD) 26.5 (2.2) years]. During subject selection, the results of screening of pathologic nystagmus (spontaneous, gaze-evoked), visual-oculomotor control (optokinetic nystagmus, smooth pursuit, saccades), and rotational vestibulo-ocular reflex suggested that all subjects had putatively normal vestibular function.

The subjects were seated on a servo-controlled rotating chair that was equipped with padding that served to delimit the upright head position (i.e., with the horizontal canals and utricular macula inclined to approximately 20° relative to the plane of rotation) and pitch forward 45° head-and-trunk tilt. The subjects were in complete darkness. A goggle with an infrared light and video camera was mounted in front of the subject's right eye to record eye movements. The left eye was covered. No particular gaze instructions were given during the part of the test when they were performing the head-and-trunk movements. However, during chair acceleration and deceleration they were instructed to keep their eyes open in the dark, to look straight ahead at an imaginary horizon, and not to try to follow imaginary points or noises in the room.

Protocol

The chair was rotating in yaw at an angular velocity of 180°/s. A metronome gave a signal every 5 s for the standardized head-and-trunk movement. At each metronome signal, the subjects tilted their head and trunk in pitch through 45° from the upright position and then return to the upright position. This movement was performed in about 1–2 s. After 1 min of rotation, during which about 12 head-and-trunk movements were made, the chair was stopped with the subjects in the upright position, and the post-rotatory nystagmus was recorded. The magnitude of this angular deceleration was 180°/s^2. After 1 min of rest the chair rotated in the opposite direction for another minute of head-and-trunk movements. The test was terminated at the request of the subjects when they experienced severe nausea or vomiting. The subjects were then placed supine on a bed for several minutes.

Based on the protocol used for the CVT of Russian cosmonauts in Star City (Krioutchkov et al. 1993; Cosmonaut C. André-Deshays, personal communication), the objective was to achieve 10 runs per session, 5 sessions per week, for 2 consecutive weeks, thus giving a total of 10 training sessions (S1–S10) including 100 runs (Fig. 1). All of the subjects were indeed exposed to ten training sessions. However, due to time constraints, session 6 (S6) was reduced to four runs instead of ten. The total number of runs per subject ranged between 45 and 83 runs due to the occurrence of motion sickness.

Motion sickness

At the end of each training session the severity of motion sickness was evaluated by the medical officer, based on a questionnaire developed by Graybiel et al. (1968). The severity of motion sickness ranged from 0 points for no symptoms to 51 points, calculated by adding the scores obtained for symptoms such as nausea, temperature, pallor, sweat, salivation, drowsiness, headache, and dizziness. In order to quantify objectively sickness levels during the course of CVT, measurements of skin pallor and salivary protein concentration were performed at the beginning, middle, and end of the CVT. Forehead skin reflectance (or skin pallor) was measured in each subject before and after the first, the fifth, and the tenth training sessions while at rest, with the aid of a spectrocolorimeter (M-508i; Minolta, Japan; Bjerring 1995). Simultaneously, salivary samples were obtained by placing sterile cotton in the subject's mouth for 1 min, based on a method used in a previous study (Igarashi et al. 1993). After centrifugation of the cotton at 3247 *g*, analysis of salivary total protein concentration was obtained by spectrophotometry (Boehringer 911; Hitashi, Japan).

Eye movements

As mentioned above, the horizontal post-rotatory nystagmus generated by deceleration of the chair after each run was analyzed, and the slow-phase peak velocity was calculated during the course of the CVT. Additional vestibulo-ocular tests were performed before, at mid-training (before S6), and on the day following the last session, then 15 days, 30 days and 60 days after the final training session (R + 1, R + 15, R + 30 and R + 60, respectively; Fig. 1). These tests include ramp accelerations and decelerations in the dark (180°/s^2 and 1°/s^2) in both the clockwise and counterclockwise directions, and caloric insufflation of both ears with a warm (49°C) or cold (25°C) flux of air (Vario-Air; Atmos, France). This permitted determination of whether the nystagmus produced by passive yaw angular acceleration of the entire body or by caloric stimulation was influenced by CVT in which the inner ear was repetitively stimulated by head movements involving Coriolis and cross-coupled angular accelerations. The very low acceleration of 1°/s^2 was utilized to assess the effects of CVT on the nystagmus threshold. These tests were performed for a long period after the end of the CVT to assess its long-term retention effects.

The signal from the video camera mounted on the subject's right eye was fed into a computer where an algorithm detected the center of the pupil for each video frame (VNG Ulmer version 2.0; Synapsis, France). This successive on-line analysis of video frames (50 Hz) allowed the recording of horizontal and vertical eye movements with an accuracy of about 0.1°. For calibration, the left

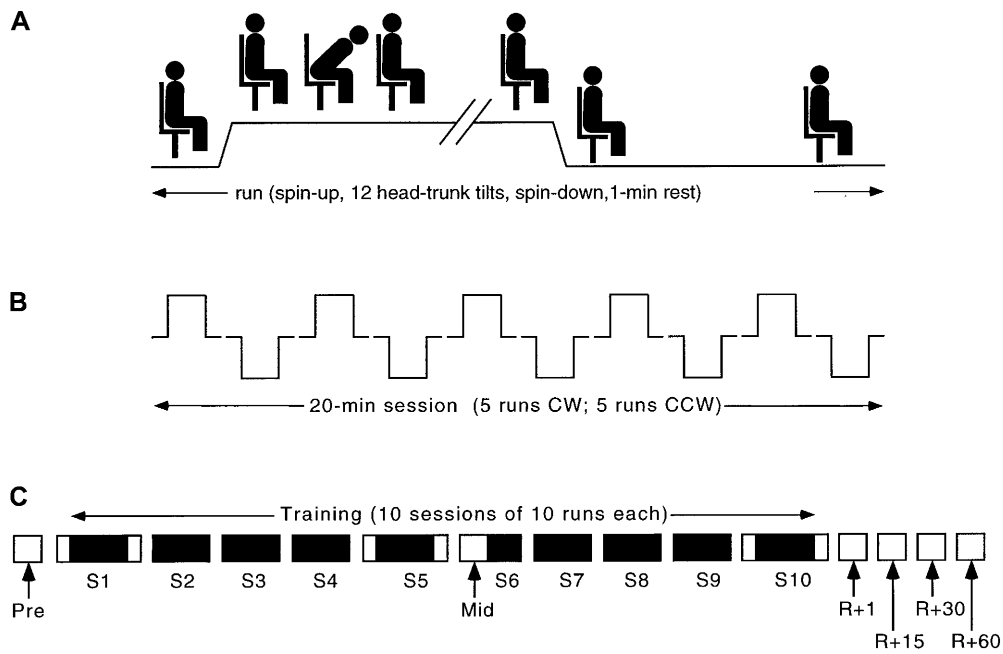

Fig. 1 **A** During each run: (1) the chair was accelerated up to 180°/s, (2) the subjects performed 12 head-and-trunk movements in about 1 min (only one head-trunk tilt is shown on this diagram), (3) the chair was decelerated at 180°/s^2 with the subjects upright, and (4) subjects were at rest for 1 min. **B** One training session included ten runs with rotation alternatively in the clockwise (*CW*) and counterclockwise (*CCW*) direction. **C** The objective was to expose the subjects to ten sessions (*S1–S10*) of ten runs each. Session S6 included a maximum of only four runs. The severity of induced sickness and post-rotatory nystagmus was evaluated during the course of the cosmonaut vestibular training (CVT; **C**, *filled rectangles*). Saliva samples were taken before and after S1, S5 and S10. In addition, per- and post-rotatory and caloric nystagmus were tested before (Pre), at mid-training just before S6 (*Mid*), and 1 day (*R+1*), 15 days (*R+15*), 30 days (*R+30*), and 60 days (*R+60*) after the final training session

eye was uncovered and the subjects were asked to look with the left eye at four wall-mounted targets subtending 20°. To quantify the characteristics of the nystagmus dynamics, the delay between the chair acceleration/deceleration and the first beat of nystagmus, the duration of the primary phase of nystagmus (i.e., the delay between the stimulus onset and the reversal of nystagmus), and the peak slow-phase velocity of both rotatory and caloric nystagmus were calculated.

Statistical analysis

Analysis of variance (ANOVA) with post-hoc *t*-tests and calculation of correlation coefficients were performed using Super-Anova and StatView (Abacus Concepts, Berkeley, Calif., USA) statistical analysis software packages, respectively. A criterion value of $P \leq 0.05$ was used for hypothesis testing, unless indicated otherwise. The results are presented as the mean (SEM).

Results

Motion sickness

Most of the subjects experienced severe motion sickness symptoms during the first 3 training sessions, corresponding to approximately 12 runs on average. The severity of symptoms decreased thereafter. The correlation coefficient between the motion sickness score on the Graybiel scale and the number of runs was $r=-0.61$ ($P<0.01$). After 30 runs, motion sickness points scored about 50% lower than noted during the first runs. Three of the 10 subjects were even symptom free after 30 runs (Fig. 2).

Univariate repeated-measures ANOVA analysis indicated that forehead skin reflectance (skin pallor) increased significantly for all subjects after the first training session (S1) compared to the control measurements (Fig. 3). Subsequent changes were not significant. When averaged across subjects, the control level of total protein concentration in saliva before sessions S1, S5 and S10 was 0.46 (0.24) g/l. There were large inter-

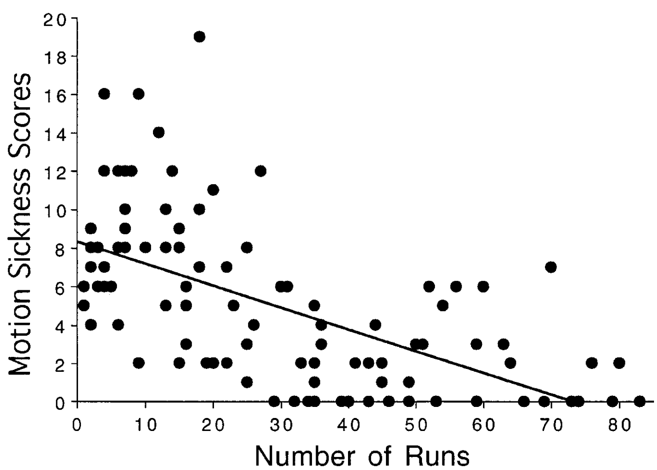

Fig. 2 Severity of induced sickness for each subject during the course of CVT, as assessed by points according to the symptoms scale defined by Graybiel et al. (1968), with the fitted regression line. The maximum possible score is 51

individual differences (0.15–1.26 g/l). Calculation of Pearson's coefficient indicated no significant correlation between individual pre-session control levels of salivary total protein and post-session motion sickness scores ($r = -0.23$). This result is in contrast with a previous study (Igarashi et al. 1993) in which an inverse correlation was noted ($r = -0.74$) between control total protein concentration and time to reach nausea for the same stimulus. In agreement with this previous study, however, salivary total protein concentration was systematically higher after the training sessions compared with the pre-stimulus control level before the sessions, but this increase was only significant after S1 (Fig. 3).

Vestibulo-ocular responses

The head movement involved a natural acceleration and deceleration in the pitch plane. However, since the body was rotating in yaw, the horizontal semicircular canal lost angular velocity so that the subject experienced rotation in yaw, and simultaneously, the anterior and posterior canals came into and then out of the plane of rotation, so that the subject also experienced roll motion, in addition to the pitch and yaw motions.

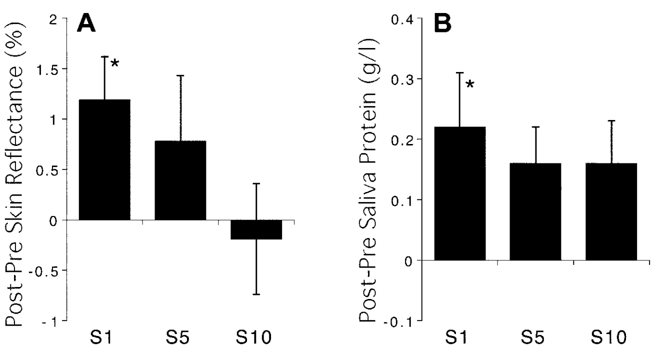

Fig. 3 Effect of CVT on skin reflectance (**A**) and salivary total protein concentration (**B**). The values reflect averages for all ten subjects of the differences in the measurements made after sessions S1, S5, and S10, and those made just before. *Error bars* indicate standard error of the mean. $*P < 0.05$ relative to control values before rotation

Tangential Coriolis accelerations were also generated during such a head-and-trunk movement, which acted on the otolith organs. A radial, centripetal acceleration was also generated when the head tilted forward, moving away from the axis of rotation, which created otolith stimulation associated with a pitch head movement. As a consequence of this complex pattern of stimulation and sensation, the eye movements that occurred during the head movement had vertical, horizontal, and torsional components (Benson 1982). A decrease in the intensity of eye movements was clearly visible during the head-trunk tilts throughout the CVT. However, since our eye movement analysis technique was limited to the horizontal and vertical eye motion components, we focused our study on the horizontal post-rotatory nystagmus generated by the chair deceleration at the end of each run. The nystagmus peak slow-phase velocity and duration decreased throughout the CVT (Fig. 4). Nystagmus peak slow-phase velocity and duration during the last training session were 31.7% and 28.9% lower ($P < 0.01$) than those measured at the beginning of CVT, respectively.

Nystagmus results from the vestibulo-ocular responses to rotational tests performed before, at mid-training, and after the training, are shown in Fig. 5. According to a repeated-measures ANOVA, the peak velocity and duration of horizontal nystagmus generated by passive yaw acceleration/deceleration (180°/s^2) were significantly reduced by 28% and 22%, respectively, at mid-training compared to the values measured before training (Fig. 5A, B). This reduction was still significant when tests were performed at R + 60 (20% for peak velocity, 15% for duration).

The effects of CVT on nystagmus threshold were determined by measuring the delay in the appearance of the first beat of nystagmus after very low yaw angular acceleration and deceleration (1°/s^2). When averaged across directions of stimulation and subjects, a significant increase in nystagmus delay relative to baseline values ($P < 0.03$) was observed just at the end of CVT (Fig. 5C). Nystagmus delay had returned to normal by R + 30 days.

These results indicate no decrement in the nystagmus reaction to caloric stimulation. Caloric nystagmus

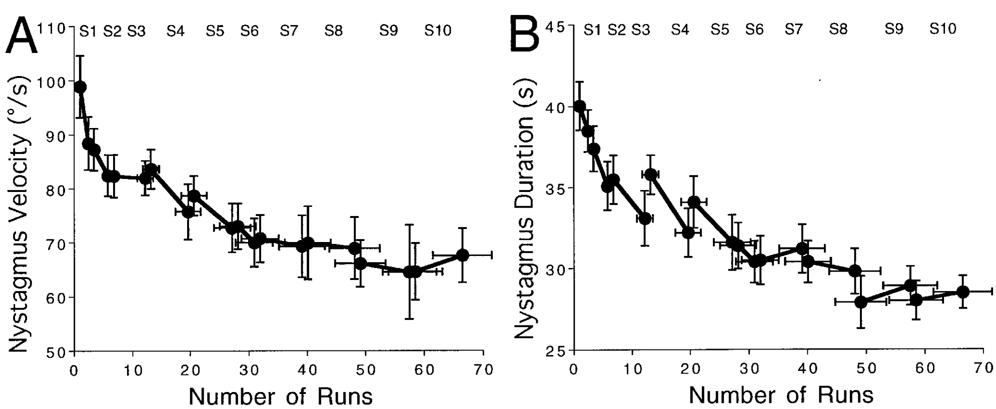

Fig. 4 Average of nystagmus peak slow-phase velocity (**A**) and duration (**B**) measured during chair deceleration during the first and the last run of each training session (S1–S10) for ten subjects. *Error bars* indicate standard error of the mean for both the nystagmus parameters (y-axis) and the corresponding cumulative number of runs (x-axis)

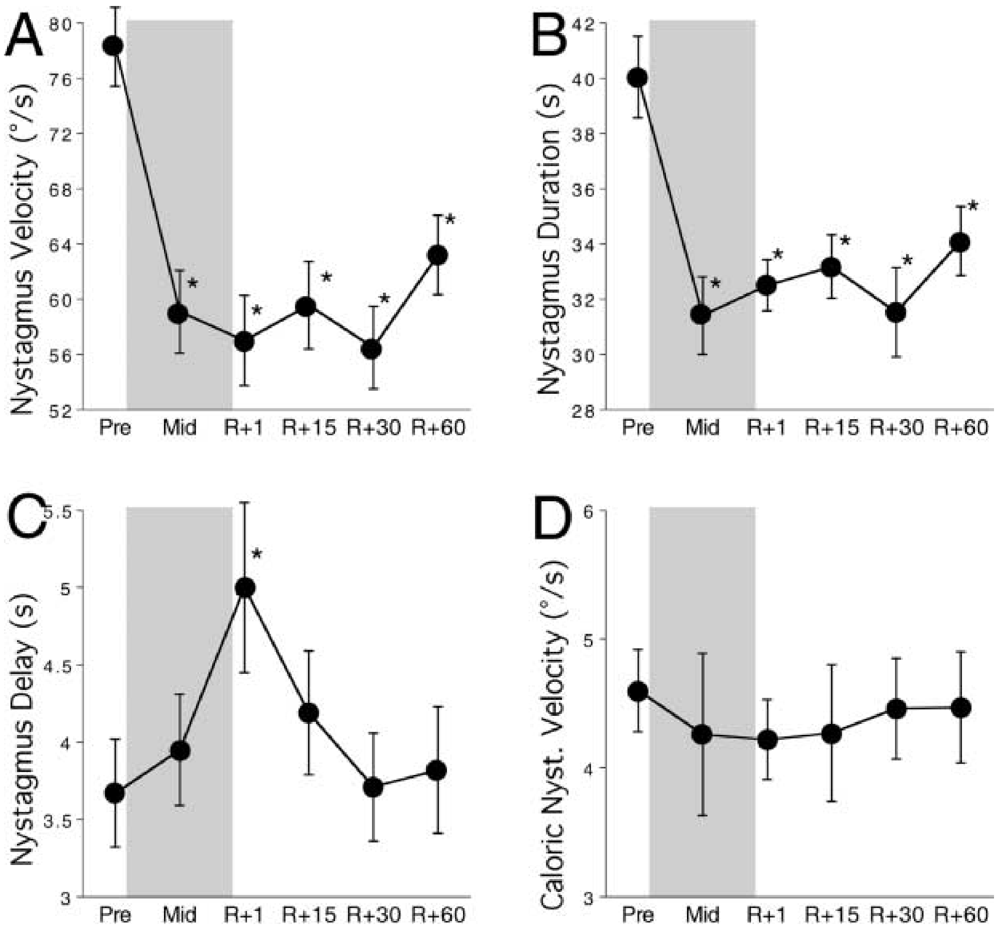

Fig. 5A–D Results of the vestibulo-ocular tests performed before (Pre), during (Mid), and after (R + 1–R + 60) the CVT. **A**, **B** Nystagmus peak slow-phase velocity and duration, respectively, measured during chair acceleration and deceleration of 180°/s^2. **C** Delay between chair motion and the appearance of nystagmus during chair acceleration and deceleration of 1°/s^2. **D** Nystagmus peak slow-phase velocity during caloric insufflation of both ears with a warm (49°C) and cold (25°C) flux of air. The values reflect averages across directions of stimulation and subjects. *Error bars* are the standard error of the mean. (*Nyst* Nystagmus). $^*P < 0.05$ relative to pre-training values

velocity did not change throughout the training (Fig. 5D). Although some subjects showed a slight decline, some also exhibited an increase. Most subjects showed equivalent reactions before and after the CVT (Fig. 6). Habituation to repetitive head and body movements that initially produced horizontal (as well as vertical and torsional) nystagmus did not transfer to stimulation of the horizontal semicircular canals by caloric stimulation.

Discussion

The use of ground-based training procedures for the control of space motion sickness is based on the principle that the lowering of an individual's susceptibility to motion sickness in one motion environment will transfer to the space situation. The objective of the present study was not to evaluate the efficiency of CVT with regard to space motion sickness. Such a validation would be difficult and would require at least the following: (1) to obtain data on control groups (i.e., individuals not participating in the training), (2) to use subjects with the same original level of motion sickness susceptibility and/or the same spaceflight experience, and (3) to assess the severity of space motion sickness in the absence of in-flight medication. Instead, the objective of the present study was to assess the actual effects of CVT on vestibular function prior to spaceflight.

A decrease in induced sickness and nystagmus elicited by such a complex pattern of stimulation has already been described after continuous exposure of subjects to a slowly rotating room (Guedry 1965; Graybiel and Knepton 1978). Although the total number of head-and-trunk movements was about the same (about 1000) in our study as in these earlier studies, we used repetitive exposure. In addition, these previous studies did not take into account the inter-individual differences in susceptibility to motion sickness. The present study used both subjective and objective methods to quantify sickness levels and compared the effects of training across subjects having different susceptibility to motion sickness.

The salivary protein content was measured according to the method used by Igarashi et al. (1993), who found, based on data from six subjects, an inverse correlation between control baseline salivary total protein and the duration of Coriolis stimulation required to reach the nausea endpoint. Our results, which were obtained with a larger cohort of subjects, do not confirm their findings, and suggest that baseline salivary total protein levels cannot be of use in predicting an individual's susceptibility to Coriolis-induced sickness.

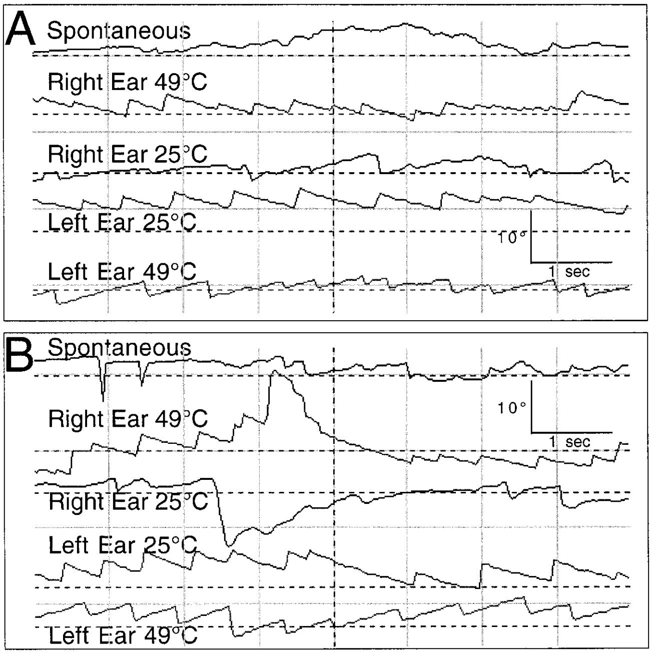

Fig. 6 Tracing of nystagmus elicited by caloric stimulation of each ear by warm (49°C) and cold (25°C) air before (**A**) and after 10 sessions (**B**) of vestibular training (total 79 runs) in 1 subject. Note the apparent lack of transfer of habituation to this stimulus

Our results show a reduction in induced motion sickness and nystagmus after CVT. The reduction in responses during CVT is presumably the result of a central vestibular habituation, as indicated by an acquisition throughout the repetition of the tests, and a retention from the end of a session to the beginning of the next session. The lowering of responses for up to 60 days after the CVT suggests that this habituation is retained for long periods. The transfer of habituation from one vestibular stimulus to another has generally been observed for repetitive stimuli that elicit the same direction of response (Collins 1973). For example, the habituation induced by repetitive clockwise velocity steps does not transfer to counterclockwise velocity steps (Clément et al. 1981). It was also noted that habituation may fail to transfer when the directions of responses are the same but they are elicited by different forms of stimulation. For example, in the cat, caloric habituation does not transfer to rotational stimuli and rotational habituation does not transfer to caloric stimuli (Collins 1964). In our study, there was no indication of transfer from the CVT to the caloric nystagmus, but the nystagmus produced by passive whole-body angular acceleration was habituated. This last result seems in contrast with a previous study using Coriolis and cross-coupled accelerations in a slowly rotating room, in which it was shown that no transfer of habituation to the nystagmus was produced by passive angular acceleration (Guedry et al. 1964). The differences in transfer of habituation between both protocols might arise from the fact that the rotation was eccentric and a variety of visual cues were present during the slowly rotating room experiment. However, since the continuous rotation of the slowly rotating room involved no starts and stops, it is most likely that the habituation of nystagmus to angular acceleration in the CVT is related to the angular velocity steps delivered at the beginning and end of each run.

Since the protocol of the CVT used in this experiment was the same as the vestibular training of the cosmonauts at Star City, a habituation of the nystagmus and symptoms is to be expected on cosmonauts exposed to this type of training. However, as observed in various types of training (Parker and Parker 1990), other vestibular-driven functions, such as self-motion perception and perception of vertical subjective and postural control, might also be affected by CVT. In the light of recent studies in which a role for the vestibular system in autonomic and respiratory control is postulated (Ray and Hume 1998; Yates and Miller 1998), some changes in vestibulo-autonomic reflexes might also be expected to occur as a result of CVT. Retention of the vestibular habituation induced by CVT may interfere with the normal adaptation of these functions to weightlessness. It is therefore recommended that space experiments on cosmonauts exposed to CVT include preflight control values before and after the CVT in order to assess its impact on the response studied.

Acknowledgements The saliva protein concentration analysis was performed at the Laboratoire de Biochimie, Hôpital Rangueil, Toulouse (Dr. Durand). We are grateful to E. Quetel (Institut de Recherche P. Fabre, Castanet-Tolosan) for his help with the skin reflectance measurements. This research was supported by the Centre National de la Recherche Scientifique (CNRS) and the Centre National d'Etudes Spatiales (CNES). This experiment was approved by the Comité Consultatif pour la Protection des Personnes dans la Recherche Biomédicale (CCPPRB) Toulouse, France.

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