



Psychophysiological assessment and correction of spatial disorientation during simulated Orion spacecraft re-entry



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ABSTRACT

The National Aeronautics and Space Administration (NASA) has identified a potential risk of spatial disorientation, motion sickness, and degraded performance to astronauts during re-entry and landing of the proposed Orion crew vehicle. The purpose of this study was to determine if a physiological training procedure, Autogenic-Feedback Training Exercise (AFTE), can mitigate these adverse effects. Fourteen men and six women were assigned to two groups (AFTE, no-treatment Control) matched for motion sickness susceptibility and gender. All subjects received a standard rotating chair test to determine motion sickness susceptibility; three training sessions on a manual performance task; and four exposures in the rotating chair (Orion tests) simulating angular accelerations of the crew vehicle during re-entry. AFTE subjects received 2 h of training before Orion tests 2, 3, and 4. Motion sickness symptoms, task performance, and physiological measures were recorded on all subjects. Results showed that the AFTE group had significantly lower symptom scores when compared to Controls on test 2 ($p = .05$), test 3 ($p = .03$), and test 4 ($p = .02$). Although there were no significant group differences on task performance, trends showed that AFTE subjects were less impaired than Controls. Heart rate change scores (20 rpm minus baseline) of AFTE subjects indicated significantly less reactivity on Test 4 compared to Test 1 (10.09 versus 16.59, $p = .02$), while Controls did not change significantly across tests. Results of this study indicate that AFTE may be an effective countermeasure for mitigating spatial disorientation and motion sickness in astronauts.

1. Introduction

The Orion spacecraft has been proposed by NASA to be the next vehicle for human exploration missions beyond low Earth orbit. The vehicle is similar in shape to the Apollo capsules but with a larger volume that will accommodate up to seven crewmembers. NASA has identified a potential risk of extreme spatial disorientation and motion sickness to future astronauts during the re-entry phase of the vehicle returning from space. Medications to control symptoms of dizziness or nausea may not be effective for all crew and often lead to adverse side effects (e.g., reduced reaction time, impaired memory and cognitive function). The purpose of this study was to test a psychophysiological training method for helping astronauts to adapt to spaceflight and re-adapt to Earth. The vehicle re-entry phase following parachute deployment will be simulated by exposing subjects to Coriolis acceleration in a rotating chair.

Autogenic-Feedback Training Exercise (AFTE), developed and patented by NASA, is a six hour physiological training procedure found to

be an effective alternative method for controlling motion sickness symptoms (Acromite et al., 2011; Cowings and Toscano, 2000; Cowings et al., 2005; Cowings, 1990; Cowings et al., 1977; Cowings and Toscano, 1982). The rationale for using AFTE to treat motion sickness was based on the assumption that there are profound autonomic nervous system (ANS) changes associated with this disorder. The relative importance of ANS responses in understanding motion sickness has been a matter of some controversy. Money (1970) in his review of motion sickness research, discussed many possible ANS changes during motion sickness, but noted correctly that there was little consistency in either procedures used or results of available research at the time. Cowings et al. (1986) measured 127 men and women during a standard rotating chair test and showed that there was in fact a significant difference in ANS responses among groups divided by motion sickness susceptibility. It has been observed in other studies (Cowings, 1990) that subjects given AFTE show smaller magnitude physiological responses to motion stimuli with faster recovery after training than before. The effect of AFTE is to normalize autonomic balance

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(complementary and reciprocal interactions of the sympathetic and parasympathetic branches of the ANS) by reducing over-reactivity to stressful stimuli and maintaining optimal response levels.

In earlier studies (Cowings et al., 2005; Cowings et al., 2001; Cowings and Toscano, 2001) AFTE has been shown to improve pilot performance during emergency search and rescue missions when compared to an untrained control group of pilots who had similar hours of flight experience. It is particularly noteworthy that AFTE improved crew coordination and communication performance, as these factors are emphasized in Cockpit Resource Management (CRM) approaches to the management of human error accidents. AFTE treatment effects were demonstrated in those dimensions involving communications with crewmembers, crew briefings, workload delegation, planning, and overall technical proficiency. Another study (Cowings and Toscano, 2000) compared AFTE to promethazine an anti-motion sickness medication currently used by space crews. AFTE was significantly more effective in preventing motion sickness symptoms without side effects, while promethazine had significant negative impact on cognitive performance (Cowings et al., 2000).

AFTE has been previously tested in space (Cowings et al., 1988; Toscano and Cowings, 1994; Cowings and Toscano, 2009) as a countermeasure for motion sickness aboard the space shuttle. Six astronauts were tested, three who received preflight AFTE (no medication) and three controls who took medication during the flight. Two of the three AFTE astronauts were asymptomatic while the third experienced only mild symptoms on the first mission day. Two of the control astronauts experienced multiple vomiting episodes on the first 3 days of the mission, and the third astronaut experienced only mild to moderate symptoms on these days. AFTE was also evaluated with two cosmonauts during a six-month mission on the Russian Space Station (Cowings et al., 1999; Cowings, 2013; Kornilova et al., 2003) as a means of improving crew performance, emotional health, and post-flight orthostatic intolerance. One cosmonaut showed good physiological control during both preflight training and self-practice AFTE sessions during the mission. During egress from the vehicle and post-flight tilt tests of orthostatic intolerance this individual did not become pre-syncope. Despite these initial successes, tests of AFTE as a countermeasure for space motion sickness were discontinued primarily because the 6-hour training program distributed over 3 weeks was too time-consuming for astronauts undergoing preflight training for a mission. To address this issue, one of the objectives of this study will be to evaluate the minimum amount of training time needed to achieve control of symptoms.

When an individual is exposed to stress (e.g., motion sickness inducing stimuli), he responds with an integrated pattern of somatic, sensory and visceral activity. This pattern of measurable behaviors, referred to as a stress profile, can be defined as observed changes in the magnitude, latency and phase relationships of those physiological responses which diverge from baseline following stimulation. No two individuals produce precisely the same stress profiles. Some individuals may show maximal responses in one or more organ system while showing no significant change in another system. Although response magnitudes or latencies of the physiological profile of an individual may differ when stimulus conditions are changed (stimulus response specificity), the basic underlining pattern remains highly idiosyncratic (Individual response stereotypy) (Andreassi, 1989). These profiles are repeatable and stable over time (Cowings et al., 1990; Cowings et al., 1986; Stout et al., 1993) and when combined with measures of performance and subjective reports (e.g., mood, symptoms experienced) enable investigators to use this converging indicators method (Cowings et al., 2007; Toscano, 2013) to characterize individual differences in responses to environmental stimuli. These methods were used in the current study to assess the impact of simulated Orion re-entry test on participants.

The effects of sensorimotor adaptations in the spaceflight environment are expressed as multiple symptoms during early exposure to

microgravity, the acute re-adaptation phase of spacecraft reentry, and for some time after returning to Earth. > 50% of astronauts experience nausea, vomiting, disorientation, and diminished visual acuity, and post-flight observations include impaired gait and/or inability to maintain balance while standing up (Heer and Paloski, 2006). Two types of countermeasures for mitigating these symptoms have been extensively tested by NASA, anti-motion sickness drugs and preflight protective adaptation (i.e., repeated exposures to motion sickness inducing stimuli). Anti-motion sickness drugs have had limited success in preventing or counteracting symptoms (Cowings and Toscano, 2000) and frequently cause debilitating side effects (Cowings et al., 2000; Heer and Paloski, 2006). The disadvantages of protective adaptation training are: 1) individuals who are highly susceptible to motion sickness tend to adapt slowly, if at all, 2) there is relatively little protection across different stimulus conditions on Earth, and 3) it does not transfer to space (Cowings, 1990; Heer and Paloski, 2006).

The effects of space motion sickness on cognitive performance have not been consistently studied. A hand operated control device is planned for use by crews during Orion vehicle descent to provide the astronaut with unrestricted access to the avionics and their applications enabling uninterrupted manual control of vehicle systems. The current study included a manual control task that subjects performed during a rotating chair test which produced angular accelerations that were similar to what crew may experience during Orion vehicle re-entry.

The study hypotheses were: 1) A rotating chair test simulating the angular acceleration effects astronauts may experience during re-entry of the Orion spacecraft will elicit spatial disorientation and motion sickness in test participants; 2) AFTE subjects will experience fewer motion sickness symptoms than no-treatment control subjects; 3) cognitive task performance of AFTE subjects will be less impaired than controls during simulated Orion tests; 4) AFTE subjects will show reduced physiological reactivity to motion sickness stimuli than the controls; and 5) a minimum of 2 h of AFTE will be effective for mitigating motion sickness and subjects will further improve their tolerance after 4 and 6 h of training.

2. Material and methods

2.1. Subjects

Fourteen men ($M = 35.5$, $SE = 2.3$) and six women ($M = 35.5$, $SE = 6.22$) participated in the study. Subjects were initially given a standard rotating chair test (described below) to determine how long they could tolerate rotation before reaching an endpoint of severe malaise. Subjects were then assigned to either an AFTE or no treatment control group ($n = 10$ per group) where the groups were matched on gender with 7 men and 3 women in each group, and motion sickness tolerance during the rotating chair test. All subjects were unpaid volunteers recruited from the workforce at NASA Ames Research Center who were medically cleared prior to their participation in the study. Informed consent was obtained from each participant following a protocol briefing by the Principal Investigator and the NASA medical monitor. There were no restrictions on diet and exercise before participation in training or tests.

2.2. Physiological measures

Physiological measures were continuously recorded during AFTE sessions and motion sickness tests. Two data encoders and associated transducers (Flexcomp Infinity, Thought Technology) were used to measure: heart rate (HR) derived from the electrocardiogram signal measured from three disposable electrodes attached to the chest; respiration rate (RR) and volume was recorded from strain gauges around the chest and abdomen; blood volume (LFPV, RFPV = left and right finger pulse volume, LTPV, RTPV = left and right toe pulse volume) was measured with photoplethysmograph transducers attached to the

index fingers and base of the second toes; muscle activity (LAEMG, RAEMG = left and right forearm extensor and LLEMG and RLEMG = left and right gastrocnemius) was monitored with three disposable electrodes at each site; skin temperature (LF Temp, RF Temp = left and right little finger and LT Temp, RT Temp = left and right large toes) was measured with thermistors taped to pinky fingers and large toes; skin conductance level (SCL) was measured from two electrodes on the left middle and ring fingers on the left hand. Cardiac output (CO) and stroke volume (SV) were recorded with an impedance cardiograph instrument (HIC-2000, Bioimpedance Technology, Inc.) using two pairs of disposable Ag-AgCl electrodes placed on the lateral sides of the neck and thorax at the level of the lower jaw and the xiphoid process, respectively. Blood pressure (SYS BP = systolic blood pressure) was monitored continuously with an inflatable cuff on the middle finger of the right hand (Finapres-Model 2300, Ohmeda). During the rotating chair tests and task training the measures included HR, RR, SCL, LF TEMP, LFPV, and LAEMG (non-dominant forearm).

2.3. Study schedule

Day	AFTE group	Control group
1	Standard rotating chair test	Standard rotating chair test
2–4	Training on manual dexterity task	Training on manual dexterity task
5	Simulated Orion reentry test 1	Simulated Orion reentry test 1
6–8	AFTE sessions 1–4	No Training
9	Simulated Orion reentry test 2	Simulated Orion reentry test 2
10–13	AFTE sessions 5–8	No Training
14	Simulated Orion reentry test 3	Simulated Orion reentry test 3
15–18	AFTE sessions 9–12	No training
19	Simulated Orion reentry test 4	Simulated Orion reentry test 4

Note: Control subjects did not report to the lab on days 6–8, 10–13, and 15–18.

2.4. AFTE sessions

AFTE involved training subjects to voluntarily control their physiological responses over a 6-hour training program. The training included twelve, 30-minute daily sessions that were distributed over 3 weeks (4 sessions per week). Daily sessions were divided into ten, 3-minute trials alternating between arousal and relaxation with a 6-minute baseline collected before and after each session. Custom software was used to record and display 24 physiological responses. The trainer selected the parameters to display to the subject as feedback. AFTE is a combination of several physiological and perceptual training techniques that include Autogenic Therapy (Schultz and Luthe, 1969), biofeedback (Miller, 1969) and progressive relaxation (Jacobson, 1938). Autogenic Therapy consists of self-suggestion exercises designed to induce specific bodily sensations (e.g., warmth and heaviness in the arms and legs). However, during AFTE training subjects were instructed to both increase and decrease response levels (i.e., bi-directional) enabling them to perceive physical sensations associated with the direction of change (Cowings, 1990). Increases in sympathetic activation during “arousal trials” were elicited immediately by presenting a stimulus to the subject (e.g., telling a joke, speaking loudly, etc.) to make his heart beat faster. Decreases in sympathetic activation during “relaxation trials” were achieved when the trainer instructed subjects to tighten and relax specific muscle groups in sequence. Subjects were given specific self-suggestion Autogenic exercises designed to elicit specific bodily sensations (e.g., heartbeat slowing, breathing regulation,

muscle relaxation, and hand-warming). Subjects were instructed to change from active-goal directed thinking during arousal to a more passive mental state during relaxation. Physiological control was achieved using operant conditioning methods (providing tones and/or visual feedback as a reward when physiological responses changed in the desired direction), and verbal instructions from the trainer.

During each session the trainer monitored the feedback displays and observed how the subject's physiological responses covaried (e.g., increases in heart rate were typically associated with peripheral vasoconstriction and increases in skin conductance). The trainer used specific criteria to guide and evaluate an individual's progress at controlling his/her responses: 1) latency - how rapidly the response changed at the start and end of a trial; 2) magnitude of change across trials; and 3) duration - maintaining response levels in the desired direction for the entire trial. The trainer could optionally provide audio feedback to subjects by setting a threshold limit that would trigger a tone. For example, heart rate increases above 80 beats per minute (bpm) turned the tone on, and when heart rate decreases below 80 the tone goes off. If the subject succeeded in turning on the tone, the trainer could gradually adjust the trigger level higher—thus “shaping” the response magnitude and direction of change. Emphasis was placed on training individuals to control those responses which changed the most during their initial motion sickness test. Physiological data were recorded during training sessions while subjects were seated in a reclining chair in a separate room. Fig. 1 shows the trainer's display monitors and video image of a test participant.

During AFTE sessions 1 to 4 (2 hour training) subjects were familiarized with the physiological responses and feedback displays and the trainer determined which type of feedback was optimal for the individual subject. Some subjects performed best with verbal feedback while others were more successful using visual and/or auditory feedback. During AFTE sessions 5 to 8 (4 hour training), the trainer gradually removed the feedback and encouraged the subject to pay more attention to internal physical cues (bodily sensations). AFTE sessions 9 to 12 (6 hour training) were devoted to maintaining skill in controlling physiological responses while introducing distractions. For example, subjects performed head movements as instructed by a pre-recorded voice without chair rotation or chair rotation without head movements. In this way, subjects learned to transfer their skill at controlling responses from the reclining chair in a quiet room to the more distracting conditions in a rotating chair.

2.5. Standard rotating chair test and symptom diagnostic scale

A rotating chair test (Acromite et al., 2011; Cowings et al., 1990; Cowings et al., 1986; Cowings and Toscano, 2000) was used to determine each subject's initial motion sickness tolerance (test duration

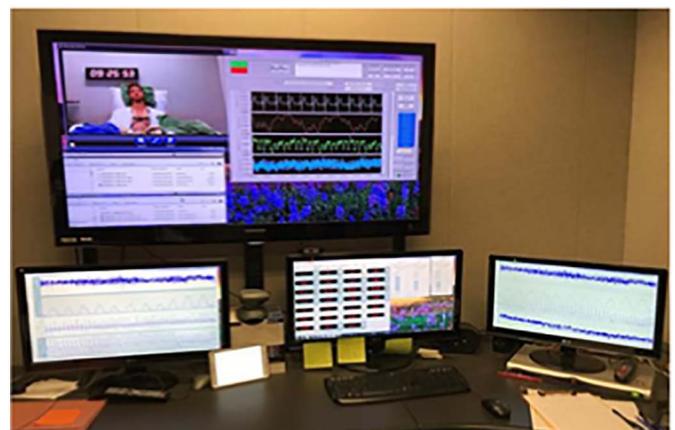


Fig. 1. Trainer's display monitors showing physiological measures and video of a test subject during an AFTE session.

before reaching their malaise endpoint) and to assign subjects to groups. Tests began with an initial speed of 6 rpm that was held at a constant speed for 5 min. The chair speeds were increased by 2 rpm/s at 5 minute intervals until the tests were terminated. During each rotational period at a constant speed the subjects executed 150 randomized head movements in four directions (left, right, front, and back). Head movement commands were computer generated and subjects made 45 degree head tilts from the head upright position. The duration to complete one head movement sequence (e.g., tilt head 'left' followed by head 'up') was 2 s. After each 5 minute period of rotation there was a 30 second pause where the subject stopped making head movements but chair rotation was continued. At this time motion sickness symptoms were rated by an observer in the room with the subject using a standard symptom diagnostic scale (Cowings et al., 2000; Graybiel et al., 1968).

The array of symptoms included subjective body warmth, dizziness, headache, drowsiness, sweating, pallor, increased salivation, epigastric awareness, epigastric discomfort, and nausea. The severity of symptoms was graded as follows: additional qualifying symptom (1 point), minimal (2 points), minor (4 points), or major (8 points). For example, a subject might describe his symptoms as subjective warmth (1 point), slight drowsiness (2 points), and severe nausea (8 points). His total score of 11 points was then used to identify the severity of motion sickness. A total score of 1 to 2 points was categorized as slight malaise, with two levels of moderate malaise (3–4 points as moderate malaise B, 5–7 points as moderate malaise A), 8 to 15 points as severe malaise, and scores equal to or > 16 as frank sickness (vomiting or retching). If the subject reported only mild symptoms the chair speed was increased 2 rpm and the subject resumed making head movements. Tests were terminated when subjects reported severe malaise (diagnostic points equal to or > 8), or the observer stopped the test if the subject was too symptomatic to continue.

2.6. Manual dexterity and mental arithmetic task

A number key pad connected to a Windows tablet was attached with Velcro to the right arm-rest (dominant hand) of the rotating chair. This task involved subtracting from 100 by 5's and entering the result into the key pad. Subjects were trained on the task on three consecutive days. Each session was 25 min in duration and included: 5-minute eyes open, 5-minute rest, 5-minute eyes open with head movements, 5-minute rest, 5-minute eyes closed with head movements. During the simulated Orion re-entry tests described below subjects were blindfolded and were asked to perform this task during the pre-test baseline and during the acceleration and deceleration phases of the test.

2.7. Simulated Orion re-entry tests

A rotating chair test was designed to simulate the angular acceleration profile crew will experience during re-entry of the Orion space vehicle. The acceleration profile was based on an engineering model that estimated the Coriolis acceleration effects that may be produced in pitch, roll, and yaw axes of the spacecraft during re-entry from when the drogue parachute is deployed to final splashdown, approximately 245 s. The model indicated that angular acceleration rates will range from about $\pm 2 \text{ rad/s}^2$ for approximately 120 s. In NASA's Human System Integration Requirements (HSIR, rev E) document the HS3065 requirement states, "that crew is not expected to tolerate sustained rotational accelerations in excess of 115 degrees/s² (2 radians/s²) without significant discomfort and disorientation." The combination of crew head motion with vehicle rotation will produce a cross-coupled angular acceleration that, above this threshold, will likely result in spatial disorientation, fuzziness of vision, and may significantly affect human performance on entry, landing and egress. Based on this requirement and the above engineering estimates of vehicle angular acceleration rates the maximum speed of the rotating chair was 20 rpm



Fig. 2. Subject performing task during simulated Orion re-entry test in a rotating chair.

(2.094 rad/s).

The simulated Orion re-entry test in the rotating chair consisted of the following steps: 1) 5 minute pre-test resting baseline (no rotation or head movements); 2) 5 min performing the manual dexterity task (no head movements or rotation); 3) increasing to 20 rpm within 20 s and maintaining 20 rpm speed for 2 min (head movements and task); 4) deceleration to 5 rpm within 15 s and remaining at 5 rpm speed for 90 s (head movements and task); and 5) deceleration to stop and remaining stationary for 75 s (no head movements or task). Fig. 2 shows a blindfolded subject spinning in the rotating chair while performing head movements and the manual dexterity and mental arithmetic task using a key pad attached to the armrest on the chair.

3. Results

3.1. Data analysis

Motion sickness symptom scores, task performance scores, and physiological measures were analyzed with NCSS-11 statistical software. These data were entered in to a repeated measures ANOVAs with Group (AFTE, no-treatment Control) as a between subject variable and Test as a within subject variable (4 Orion tests). Mauchly's test statistic was used to check for violations of the sphericity assumption and Greenhouse-Geisser corrections were applied when this assumption was violated. Significant main effects and interactions were further explored with post-hoc Tukey-Kramer tests to examine between and within group differences.

3.2. Motion sickness susceptibility

Fig. 3 shows the cumulative number of rotations achieved by each participant during the standard rotating chair test. Subjects were assigned to groups based on the number of rotations achieved during this test. Each group included 3 high susceptible (≤ 80 rotations), 3 moderate susceptible (100 to < 180 rotations), and 4 low susceptible (≥ 180 rotations) subjects. There were 7 men and 3 women participants in each group (Table 1).

3.3. Motion sickness symptom diagnostic scores

Fig. 4 shows the symptom diagnostic score group means ($\pm SE$) across four simulated Orion re-entry tests in the rotating chair. A repeated measures ANOVA with Group as a between subject variable and Test as a within subject variable yielded a significant main effect for

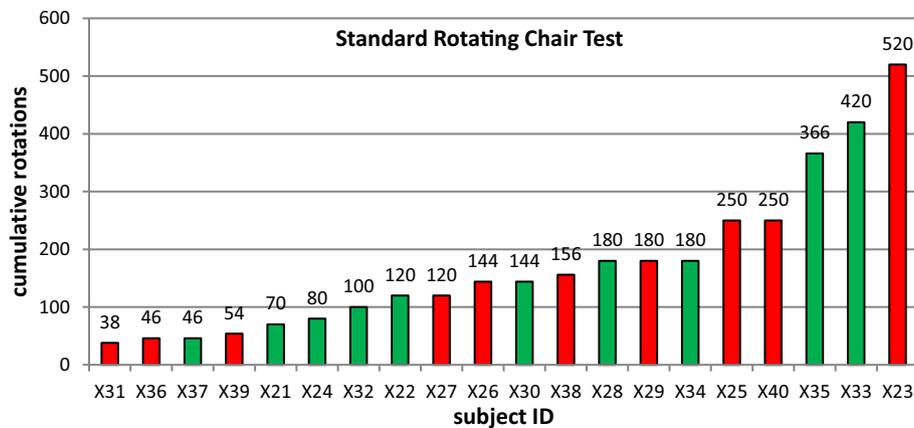


Fig. 3. Vertical bars and number of rotations achieved by each participant (red = Control subjects, green = AFTE subjects) during the standard rotating chair test. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1

Ages and rotations tolerated ($M \pm SE$) of men and women in each group during the standard rotating chair test.

Group (n)	Age: $M (\pm SE)$	Rotations: $M (\pm SE)$
AFTE (10)	35.9 (3.7)	170.6 (39.8)
Men (7)	34.0 (2.3)	190.9 (54.2)
Women (3)	40.3 (12.4)	123.3 (40.0)
Control (10)	35.2 (3.2)	176.0 (45.3)
Men (7)	37.1 (4.2)	183.1 (62.1)
Women (3)	30.7 (4.0)	158.7 (59.9)

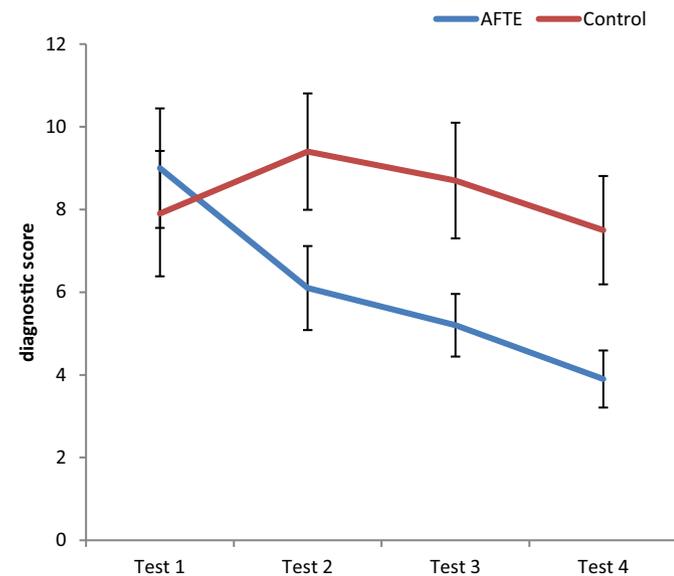


Fig. 4. Symptom diagnostic score group means ($\pm SE$) across tests.

Test; $F(3, 24) = 5.42, p = .02, \eta_p^2 = 0.40$, and a significant Group \times Test interaction; $F(3, 24) = 5.09, p = .03, \eta_p^2 = 0.39$. Post hoc tests between groups were not significant on test 1 (no training); however a significant difference was revealed on Test 2 (after 2 h of training) where mean symptom scores were lower for the AFTE group ($M = 6.1, SD = 3.21$) than the Control group ($M = 9.4, SD = 4.45$) $p = .05$; on Test 3 (after 4 h of training) a further reduction in symptom scores was observed for AFTE ($M = 5.2, SD = 2.39$) compared to the Control group ($M = 8.7, SD = 4.42$) $p = .03$; and finally on Test 4 (after 6 h of training) symptoms continued to decrease for AFTE ($M = 3.9, SD = 2.18$) compared to the Control group ($M = 7.5, SD = 4.14$) $p = .02$. Post-hoc pairwise comparisons for the AFTE group were

significant on Test 1 versus Test 3 ($p = .01$); and Test 1 versus Test 4 ($p = .001$). There were no significant differences across tests for the Control group.

3.4. Manual dexterity and mental arithmetic task

Data from keypad entries were converted to accuracy scores (number of entries – number of errors and expressed as a percentage) and response speed scores (number of seconds per response). Fig. 5 shows accuracy and response speed scores during the last task training session and the four simulated Orion re-entry tests. The repeated measures ANOVA performed on accuracy scores with Group as a between subject variable and Test as a within subject variable (5 levels-task training 3 and 4 tests) yielded a significant main effect for Test; $F(4, 71) = 9.51, p < .001, \eta_p^2 = 0.35$, and a marginally significant Group \times Test interaction; $F(4, 71) = 2.41, p = .09, \eta_p^2 = 0.12$. Although post-hoc tests between groups were not significant, accuracy scores for the AFTE group were less impaired than the Control group on Test 1 (85% versus 75%) and Test 2 (83% versus 73%). Pairwise comparisons for the AFTE group indicate a non-significant decrease in accuracy on Test 1 (85%) when compared to their last task training session (96%), while the Control group showed significant decreases on Test 1 (75%) and Test 2 (74%) when compared to their last task training session (92%), $p = .002$ and $p < .001$, respectively. No significant differences on accuracy were observed for either group on Test 3 and Test 4 when compared to the last task training session. The repeated measures ANOVA of response speed revealed a significant main effect for Test, $F(4, 71) = 5.84, p < .005, \eta_p^2 = 0.25$, and the Group \times Test interaction, $F(4, 71) = 3.29, p < .04, \eta_p^2 = 0.16$. Post-hoc tests between groups showed that response speed (seconds per response) on Test 1 was significantly slower for the Control group than the AFTE group (3.88 versus 2.15) $p = .02$, while Test 2, Test 3, and Test 4 were non-significant. Pairwise comparisons across tests were not significant for the AFTE group, however Controls showed a significantly slower response speed on Test 1 (3.88) when compared to their task training session (1.85), $p = .003$, with no significant differences on Test 2, Test 3, and Test 4.

3.5. Individual physiological stress profiles

Standard rotating chair tests enabled investigators to identify which physiological parameters changed as the stimulus increased for each individual and to determine where emphasis was placed during training. In the psychophysiology literature “individual response stereotypy” is defined as the tendency of individuals to evidence particular physiological response patterns from one condition or situation to another. Our method for describing an individual’s stress profile involves a

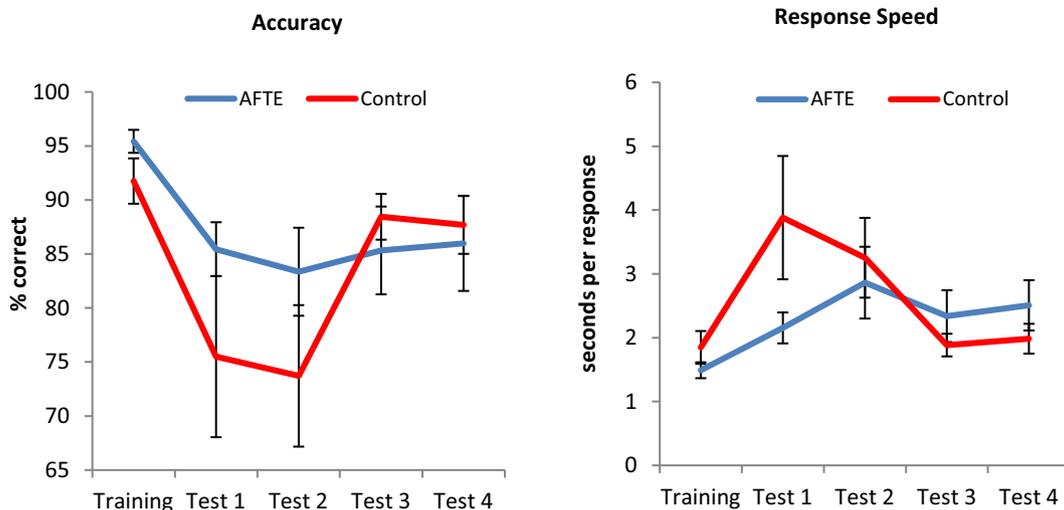


Fig. 5. Group means ± SE of accuracy (% correct) and response speed (seconds per response) during the final day of task training and the 4 simulated Orion re-entry tests.

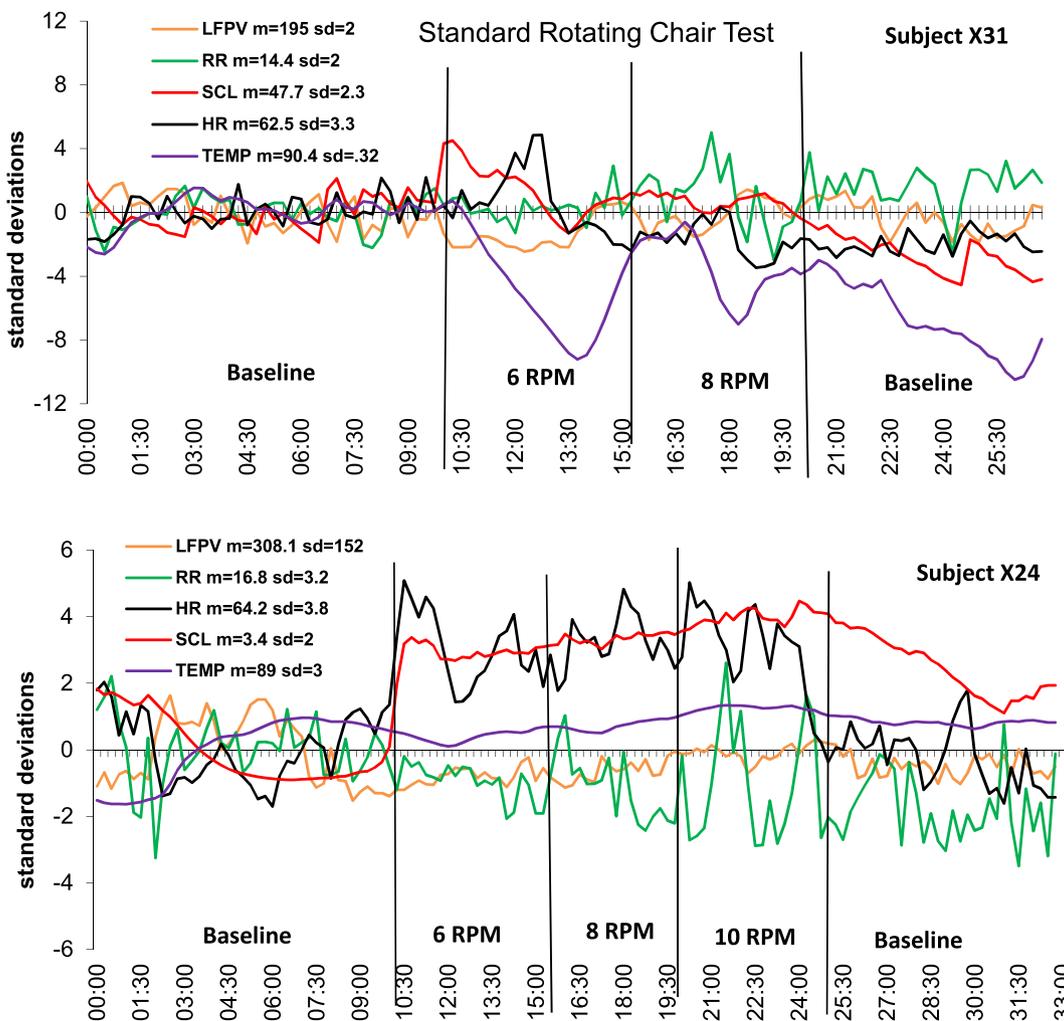


Fig. 6. Z-scores of physiological stress profiles of two subjects during a rotating chair test. Numbers in the legend represent the baseline means and standard deviations for each variable. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

z-score transformation of the physiological measures such that an individual's response change to a stimulus is adjusted relative to his/her resting baseline mean and standard deviation, therefore $z = (x - \text{mean baseline}) / \text{standard deviation baseline}$. This method enables researchers to plot all physiological variables on the same y-ordinate to

identify which response had the largest magnitude change, how the responses covary with one another, and the rate of recovery or return to baseline when the stimulus is removed (i.e., rotation has stopped). Fig. 6 shows the physiological response profiles of two participants during the standard rotating chair test. In the upper graph the largest

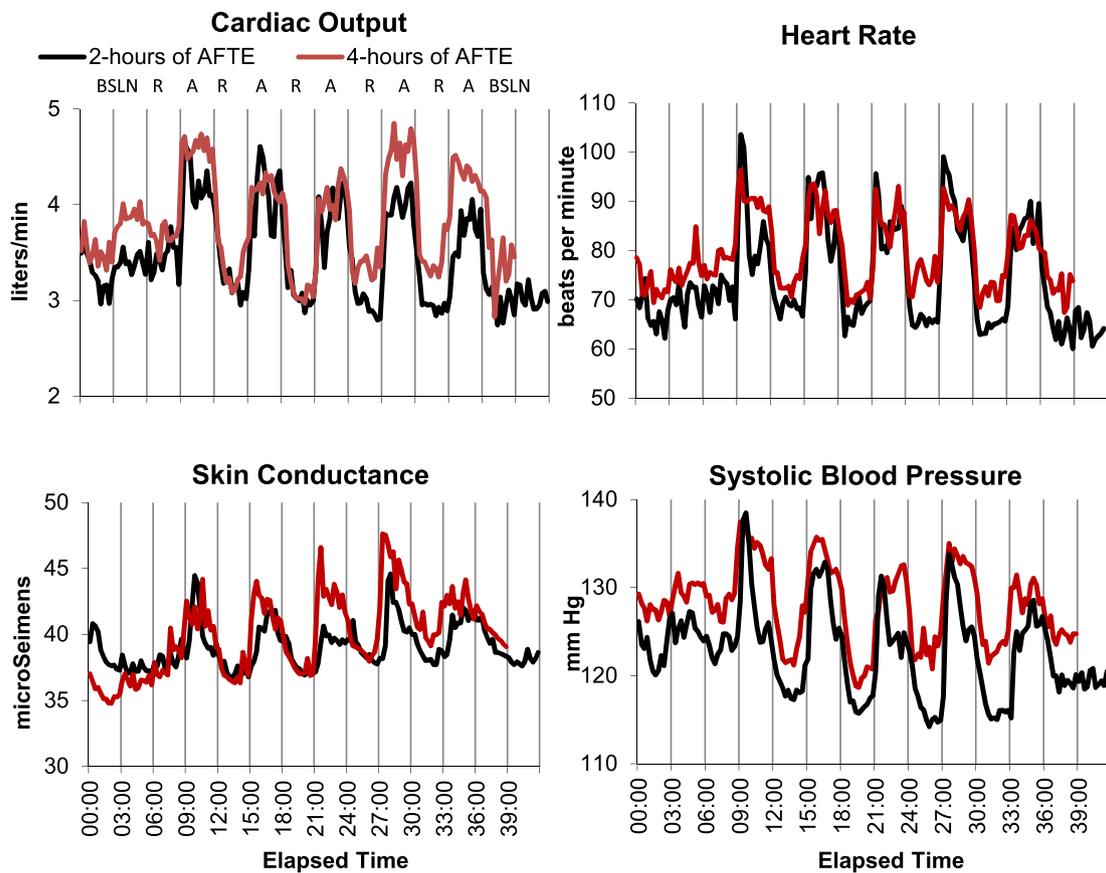


Fig. 7. Example of physiological responses of one subject after 2 and 4 h of AFTE. Note that the trials alternated between 3-min of ‘relaxation’ (R) and 3-min of “arousal” (A) beginning at 6-min with a relax trial.

magnitude response for this subject was a decrease in peripheral skin temperature (purple line). At the start of rotation (6 rpm) SCL abruptly increases and then decreases to baseline levels, HR slowly increases and decreases below baseline levels, while TEMP decreases with little evidence of recovery to pre-test baseline levels. In contrast, the lower graph is data from another subject showing a large and sustained increase in HR and SCL, with a smaller magnitude increase in TEMP than HR and SCL.

A NASA technical memorandum (Cowings and Toscano, 2017) contains z-score physiological profiles of all study participants during standard rotating chair tests and Orion tests, and the physiological data of AFTE subjects during training sessions.

3.6. Physiological data of individuals during AFTE

One objective of this study was to determine the minimum amount of training needed to demonstrate effective control of physiological responses to mitigate motion sickness symptoms. The results showed that AFTE subjects reported significantly fewer symptoms after 2 h of training (Test 2). Fig. 7 is an example of the level of physiological control achieved by one subject after 2 h (AFTE session 4) and 4 h (AFTE session 8) of training. This subject showed an immediate increase in response levels at the start of each arousal (A) trial, was able to maintain relatively stable levels over the duration of the trial, and then decrease levels at the start of each relaxation (R) trial. Further evidence of success in controlling physiological responses can be seen during rotating chair tests where subjects apply their acquired skill to reduce motion sickness symptoms. This individual showed an overall improvement in symptom scores across tests: Test 1 (10 points – severe malaise), Test 2 (7 points - moderate malaise), Test 3 (5 points - mild), and Test 4 (1 point – minimal).

AFTE training effects over sessions 1–8 for each subject were quantified as a slope fitted to the successive difference between arousal (increase HR) trials and relax (decrease HR) trials. Difference scores were calculated as 3-min means of the arousal and relax trials which were equally distributed over each training session (5 relax and 5 arousal trials) resulting in 5 scores for each physiological variable. A total of 40 difference scores (5 trials per session × 8 AFTE sessions) were used in the analysis where a line (linear function $y = ax + b$) was fitted to the successive difference scores. With this method, successful training is reflected in a larger heart rate increase in arousal as compared to relax trials (increasingly larger magnitude changes) over the training sessions, yielding a positive slope.

The slope value (a) reflects performance gains with bigger training effects resulting in more positive values. Therefore, the training effect can be described as the increase in the change between arousal and relax trials from AFTE sessions 1 to 8. Table 2 shows the physiological training effects (significant positive and negative slopes) for each subject over AFTE sessions 1–8. Negative slopes for RR indicate that subjects were better able to maintain constant respiration rates and volumes and therefore made smaller changes across trials and sessions. The column on the right of Table 2 shows how many subjects gained significant control of specific physiological measures and the row on the bottom shows how many variables each individual had gained significant control. Note that for some individuals no significant change occurred over the 8 days of training because they were able to make correct responses on the first two AFTE sessions and maintained this degree of control throughout for all training sessions.

3.7. Physiological data of individuals during Orion tests

Fig. 8 is an example of a highly susceptible AFTE subject's

Table 2
Significant physiological training effects over 8 AFTE sessions.

Measure	X21	X22	X24	X28	X30	X32	X33	X34	X35	X37	# subjects
LFPV	32.2 ^a					35.56 ^a			12.1 ^a		3
RFPV	16.34 ^a										1
LTPV	9.97 ^a					7.37 ^a	14.3 ^a	3.43 ^a	2.89 ^a		5
RTPV	17.98 ^a	1.8 ^a				10.5 ^a			4.07 ^a		4
HR	0.32 ^a	0.41 ^a	1.18 ^a	0.53 ^a	0.32 ^a	0.57 ^a				0.41 ^a	7
SCL		0.15 ^a								0.52 ^b	2
RR			-0.18 ^b	-0.12 ^b	-0.19 ^b	-0.11 ^b	-0.18 ^b	-0.26 ^b	-0.29 ^b	-0.22 ^b	8
RF Temp	0.15 ^a								0.12 ^a		2
LT Temp						0.18 ^a					1
RT Temp						0.16 ^a	0.09 ^a			0.54 ^a	3
SBP			0.81 ^a								1
CO	0.02 ^a	0.014 ^a	0.054 ^a	0.032 ^a	0.023 ^a	0.21 ^a			0.36 ^a	0.04 ^a	8
SV	0.08 ^a								0.65 ^a		2
# measures	8	4	4	3	3	8	3	2	7	5	

^a Positive slope.
^b Negative slope.

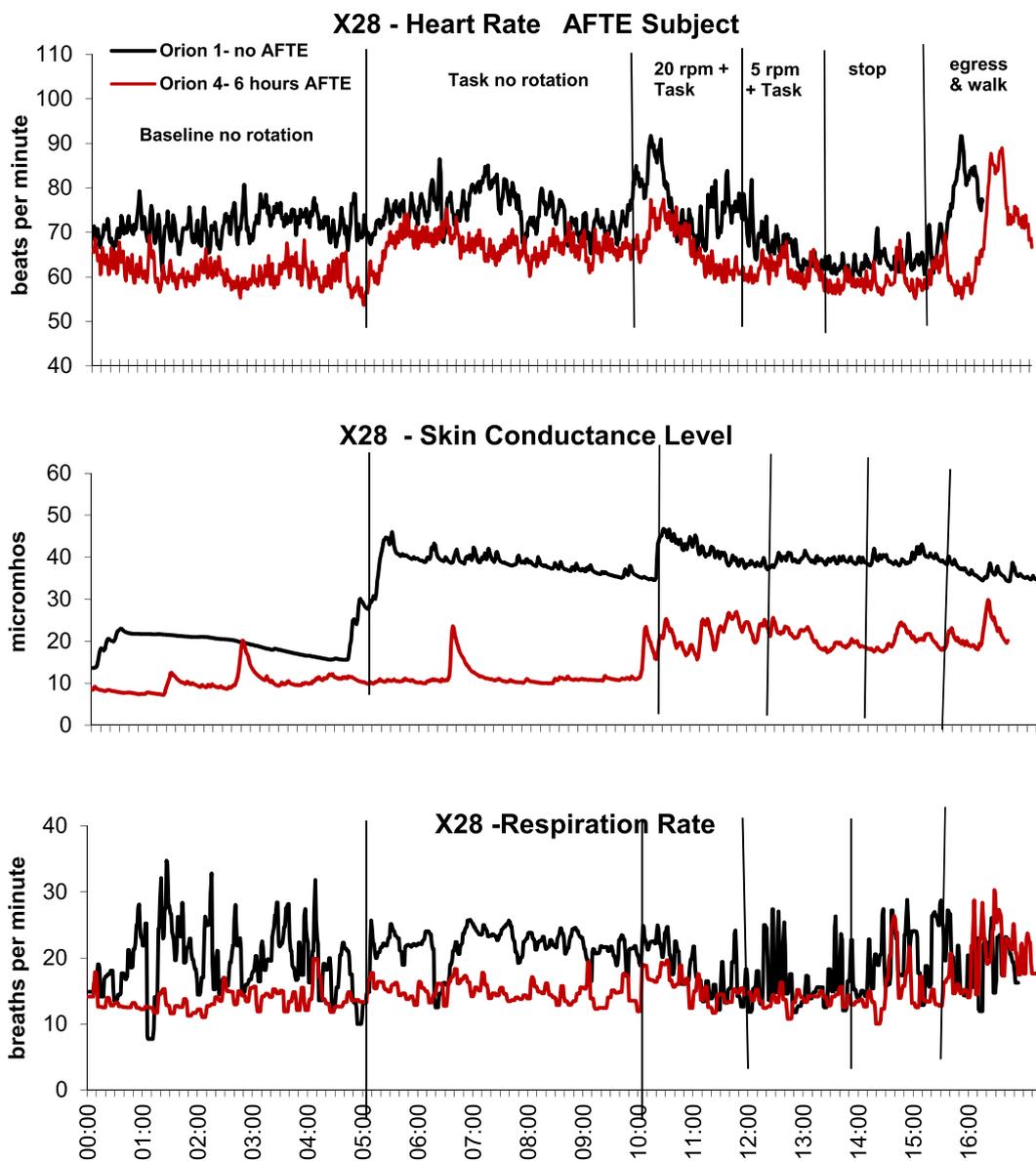


Fig. 8. Data of a highly susceptible subject before training (test 1) and after 6 h of AFTE (test 4).

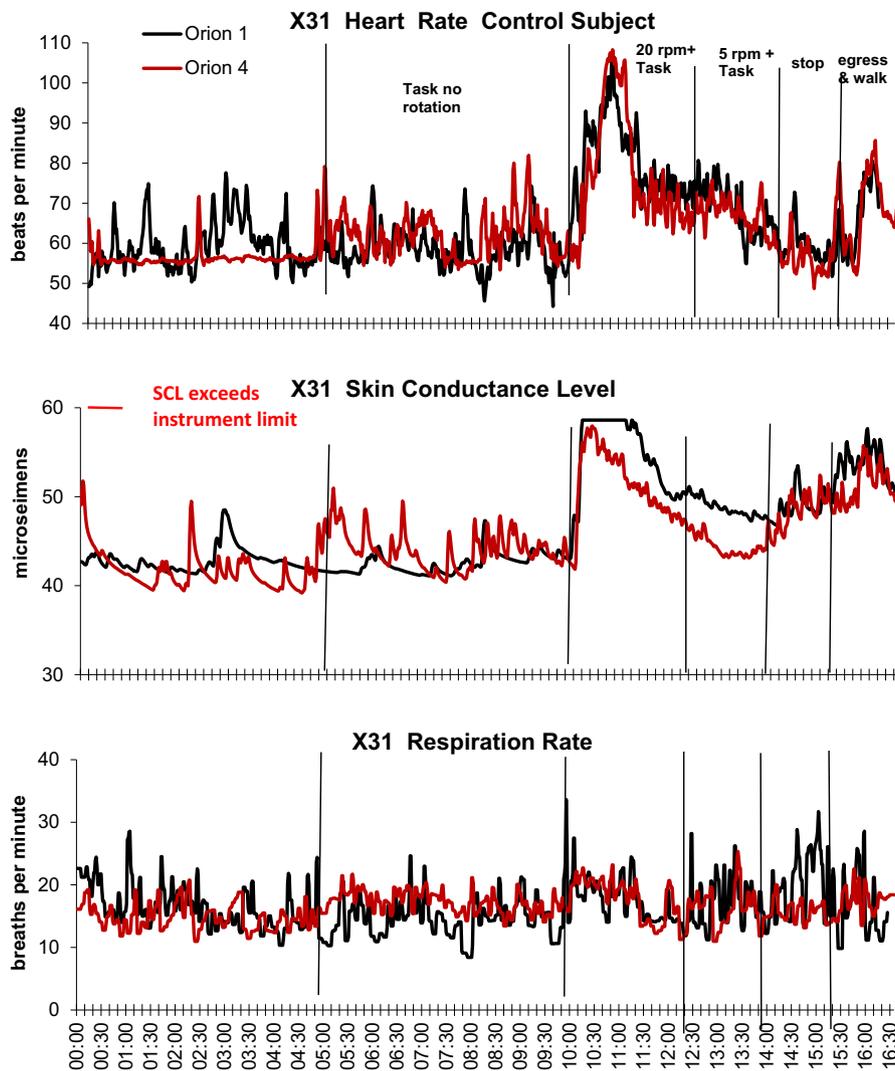


Fig. 9. Data of a highly susceptible control group subject during Orion tests 1 and 4.

physiological responses during Orion tests 1 and 4 showing reduced levels of HR, SCL, and RR after training.

Fig. 9 is an example of a highly susceptible Control subject's physiological responses during Orion tests 1 and 4. This subject's responses were unchanged across tests. On both tests HR reached 100 bpm, SCL reached or exceeded maximum readable levels of the recording device (60 μ S) and respiration was similar.

3.8. Physiological data of groups during Orion tests

Means for heart rate, respiration rate, skin conductance and skin temperature were calculated for the baseline (5-minute) and 20 rpm (2-minute) intervals of each test. Change scores (20 rpm minus baseline) were then computed for each variable, and then repeated measures ANOVAs with Group as a between subject variable and Test (4 levels) as a within subject variable were performed on the obtained values. A main effect for Tests, $F(3, 24) = 2.98, p = .05, \eta_p^2 = 0.27$, and a significant Group \times Test interaction was found for heart rate, $F(3, 24) = 3.90, p = .03, \eta_p^2 = 0.33$; and marginal significance for respiration rate, $F(3, 24) = 2.79, p = .06, \eta_p^2 = 0.26$. There were no significant main and interaction effects for skin conductance and skin temperature. Post hoc tests between groups revealed heart rate change scores on Test 1 (no training) were significantly larger for the AFTE group compared to the Control group (16.51, 8.89), $p = .005$, suggesting AFTE participants were more physiologically reactive for heart

rate. Pairwise comparisons of the AFTE group indicated trends toward smaller heart rate change scores on Test 2 versus Test 1 (12.47, 16.51), Test 3 versus Test 1 (12.21, 16.51), with a significant difference on Test 4 versus Test 1 (10.09, 16.51), $p = .02$, while there were no significant differences across tests for the Control group. These findings suggest the effect of AFTE training was to reduce heart rate reactivity and with additional training this effect is better. Between group comparisons of respiration rate change scores were significantly smaller for the AFTE group compared to the Control group, but only on Test 3 (0.83 versus 3.86), $p = .02$. Although pairwise comparisons were not significant for either group, trends across tests indicate smaller respiration rate change scores for the AFTE group than the Control group. One explanation for this result is that AFTE participants were trained to maintain their breathing rate between 12 and 15 breaths/min during the baseline and for the entire duration of the test.

4. Discussion

The first hypothesis stated that a rotating chair test simulating the angular acceleration effects astronauts may experience during re-entry of the Orion spacecraft will elicit spatial disorientation, and motion sickness. Sixty percent (12/20) of the participants experienced severe malaise when the chair speed was at 20 rpm producing Coriolis effects similar to what would occur during the parachute deployment phase of the returning Orion spacecraft.

The model used for designing the rotating chair test was incomplete because it omitted other important variables that may negatively impact crew when returning from space. A limitation of this study was that high gravitational loads that crew will experience during the 20 minute vehicle re-entry phase was not included. Another limitation, and more importantly, is that returning crew will have a deconditioned cardiovascular system (i.e., a weaker heart and reduced vascular responsiveness), and changes to other autonomic responses due to prolonged periods of exposure to zero gravity in space. To simulate these physiological effects on Earth requires placing test participants in 6° head-down bed-rest for extended periods of time, exposing subjects to high gravity in a centrifuge simulating vehicle re-entry, and finally exposing them to the 20 rpm angular accelerations in a rotating chair simulating the parachute deployment phase on re-entry.

The second hypothesis was that AFTE subjects will experience fewer motion sickness symptoms than no-treatment Control subjects. As expected there were no significant group differences found on Orion Test 1 where the AFTE group received no training. However, significant group differences were found after 2, 4, and 6 h of AFTE (Orion Test 2, 3 and 4). Within group effects showed that as training time increased AFTE subjects continued to improve their physiological control with a further reduction in symptoms, while control subjects did not change significantly. These results support our supposition that AFTE facilitated adaptation to this stimulus.

The third hypothesis stated that cognitive task performance of AFTE subjects will be less impaired than Controls during simulated Orion reentry tests. Despite non-significant group differences in accuracy and response speed scores, the data indicate stable performance scores for the AFTE group across Orion tests. Performance of the Control group was impaired on the first 2 tests and then improved on tests 3 and 4. When Orion test 1 was compared to the last task training session (where there was no rotation and subjects reached a learning plateau), both groups showed a decrement. These results highlight a third limitation of this study. The task was not a good representation of tasks astronauts will be expected to perform during actual vehicle re-entry (e.g., controlling avionics, communications with ground control, and monitoring life support). A more difficult and challenging performance task (in spaceflight deconditioned crews) would likely have resulted in greater performance impairment emphasizing the need for an effective countermeasure.

The fourth hypothesis stated that AFTE subjects will show reduced physiological reactivity to motion sickness stimuli than the Controls. Evidence supporting this hypothesis was that AFTE subjects had significantly lower heart rate and respiration rate changes after training than before training. Similar non-significant trends for decreased skin conductance level were observed. Measures of peripheral circulation (skin temperature, pulse volume) showed trends of vasodilation on the last two tests. However, physiological reactivity of Control subjects to repeated exposures to this stressor did not change significantly. The observation of large inter subject variability is elucidated by the principle individual response stereotypy. The results showed that most AFTE subjects gained control of heart rate and respiration rate, however, this should not lead to the conclusion that other parameters were unimportant. Control of SCL and/or peripheral blood flow was a more important indicator of malaise for some subjects than for others and this is not reflected in the group means. Some subjects may have only needed to control one parameter while others needed to gain control of 4 or more responses to reduce motion sickness symptoms. Because physiological responses to stress and AFTE are highly idiosyncratic, the optimal method of evaluating the effects of AFTE for a given individual is to examine his/ her response profile over days. The graphs of individual subject responses before and after AFTE were provided to illustrate these observations.

The final hypothesis stated that a minimum of 2 h of AFTE will be effective for mitigating motion sickness. Results showed that AFTE subjects significantly reduced their motion sickness symptoms after 2 h

of training, and showed further improvements in controlling symptoms after 4 and 6 h. It has been our observation that most people reach a learning plateau at controlling their physiological responses within the first 2 h of training, however, some individuals require more time to transfer this skill to stressful or distracting situations. Additional self-administered practice sessions while at home may help to improve physiological control for these individuals. This could be accomplished by providing individuals with small, ambulatory physiological monitors that connect to a mobile device for displaying their physiological responses.

This study was designed to test AFTE as a potential countermeasure for space flight crews. Because the crew complement for each mission is small (4 to 7 individuals) the best methodological approach is to document baseline physiological response profiles and tailor appropriate countermeasures for each crewmember. By monitoring responses of individuals to specific stressors (e.g., motion sickness, high and low workload, or emotional distress) and alerting the individual when his/her responses exceed a normal range appropriate countermeasures can then be applied. NASA is developing a medical system to support crew health and performance during future long term missions. This system will include decision support tools to aid the physician astronaut in diagnosing and treating a sick or injured crewman with a potentially life-threatening medical condition (e.g., cardiac arrhythmias). The detection of adverse psychophysiological response patterns and alerting crew are well within its capabilities. Crew who had received pre-flight AFTE could practice physiological control and mitigate their own symptoms using mobile devices for physiological feedback during the mission.

The results of this study indicate that spaceflight crews could benefit by receiving a minimum of 2-h of preflight training. During deep space missions (Mars) crew will be autonomous without real-time communication with Mission Control support. These crews will need the capability to self-monitor and self-correct adverse psychophysiological responses that may occur. The AFTE countermeasure and data characterization methodology should be tested with crew in high fidelity space flight analogs (e.g., Earth based tests that simulate space craft environments and head-down bedrest) and potentially with flight crews aboard the International Space Station.

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