Layperson Physiological Tolerance and Operational Performance in Centrifuge-Simulated Spaceflight

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INTRODUCTION: Prior study has indicated that individuals of varied age, medical history, and limited-to-no experience tolerate spaceflight conditions. We sought to expand upon the understanding of layperson response to hypergravity conditions expected in commercial spaceflight by exposing subjects, following minimal training, to centrifuge-simulated, high-fidelity commercial spaceflight profiles. We further explored how these individuals perform in simulated operational activities during and following hypergravity.

METHODS: Volunteer subjects participated in up to five centrifuge runs (maximum +4.0 G_z, +4.5 G_x, 6.1 G resultant; onset rate <0.5 $G_z \cdot s^{-1}$, ≤1 $G_x \cdot s^{-1}$). Profiles included two winged spacecraft simulations with sequential and combined $+G_x/+G_z$ and two capsule simulations representing nominal $+G_x$ launch and reentry. The final profile simulated a capsule launch abort, with a more dynamic cycling of $+G_x$ exposures and oscillatory multi-axis exposures simulating parachutes and water motion. Touchscreen tablets were used to administer pattern-replication tasks during and after profiles.

RESULTS: A total of 46 subjects participated, including 4 diabetics and 9 with cardiac disease. There was increased frequency of motion sickness, subjectively associated with capsule-type profiles, and increased termination of participation compared to prior studies. There was no association between medical history, age, sex, or motion sickness history and tolerance or noncompletion. Tablet test errors were common; accuracy and time to completion were associated with age. There was no association between any time metric or accuracy and sex.

DISCUSSION: This study improves understanding of layperson tolerance in commercial spaceflight analog conditions, and the capsular profiles broaden the applicability of the findings. The frequency of task errors highlights the potential for mistakes in operational activities when performed by laypersons.

KEYWORDS: human centrifuge, hypergravity, commercial spaceflight, acceleration, task performance, spaceflight participant, G-exposure.

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Layperson spaceflight participants (SFPs), including those of variable age or with pre-existing medical conditions, may present additional risk factors in the hypergravity environment, with potential decrements to hypergravity tolerance or even the ability to carry out moderately complex tasks in emergency or high-stress operational scenarios. Previous studies[2,4,5] have indicated that individuals of varied age and limited-to-no experience in an operational environment, including those with well-controlled medical conditions, can physiologically tolerate hypergravity exposures simulating commercial spaceflight launch and landing profiles. Even so, additional data are desirable to improve upon our understanding of layperson responses to spaceflight or analog experiences, to better characterize risk for individuals with medical histories novel to the space environment, and to understand the operational performance capabilities of laypersons in spaceflight and analogs.

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Studies have identified factors of interest to the commercial spaceflight community, such as an association between known inclination toward motion sickness and the prevalence of anxiety responses during centrifuge spaceflight simulation,[14] or the finding that higher-fidelity training, even when abbreviated, appears to be as effective in ensuring physiological tolerance of nominal flight as longer, stepwise training experiences.[2] However, previous literature has lacked tangible evidence regarding operational performance of laypersons in such environments, particularly when under stress or in off-nominal circumstances. Efforts to simulate emergencies or operational inputs in prior studies have been limited primarily by fidelity,[2,3] where simulated emergency or operational tasks bear little resemblance to actual in-flight human-vehicle interfaces or emergency actions. While many historical vehicle user-interfaces have consisted primarily of manual switches, newer vehicles have increasingly introduced touchscreen devices and more streamlined user interfaces.[7,12,15] Modern "smart" devices allow for the incorporation of decision-support software, such as binary (yes/no) decision trees; even so, associated challenges include the lack of manual or tactile feedback, lack of familiarity or comfort with advanced technological devices, or similar.[12] Appropriate activation and usage of such smart devices for operational actions in an emergency, or referencing of appropriate procedures and following referenced instructions, may be challenging for unfamiliar or minimally trained layperson SFPs.

Here, we sought to expand upon the understanding of how inexperienced individuals of varied age and prior medical history respond to hypergravity conditions similar to those of commercial spaceflight. In particular, we sought to expose laypersons, following minimal training without introductory stepwise hypergravity exposure, to centrifuge-simulated, high-fidelity spaceflight profiles representative of both capsule and winged vehicle designs. As prior studies have primarily focused on winged vehicle spaceflight simulations, the addition of capsule profiles improves the applicability of the data to a broader range of vehicle designs and provides additional understanding of layperson response to capsule-type hypergravity profiles. We further sought to characterize layperson performance on simulated operational activities during and immediately following hypergravity exposure in an effort to model a realistic experience that SFPs might face during commercial spaceflight.

METHODS

Subjects

A prospective cohort study, approved by the University of Texas Medical Branch Institutional Review Board, was designed to recruit volunteers for physiological training in a centrifuge at the National Aerospace Training and Research (NASTAR) Center centrifuge (Southampton, PA). Volunteer registrants, age ≥18 yr, were asked to complete a medical history questionnaire and undergo a physical exam by their personal physicians with guidance and forms provided for this purpose. The instructions, process, and forms used were similar to the guidance and materials provided for Federal Aviation Administration (FAA)-approved exams performed by Aviation Medical Examiners and were identical to the guidance and documentation used in prior studies of this type.[2,4,13] All participants were required to provide a resting electrocardiogram (ECG).

An Aerospace Medicine-certified study investigator, specifically a board-certified Aerospace Medicine physician with experience in centrifuge and spaceflight operational medical support, reviewed all medical documentation. Participants could be approved directly, be requested to undergo further tests or provide more records, or be excluded altogether depending upon their medical status, history, and physical findings. The screening process was similar to that described in previous publications.[2,4,13] Participants with significant risk factors, such as a history of medical diseases including but not limited to hypertension, diabetes, back and neck disorders, pulmonary disease, dysrhythmias, and other heart conditions, were required to provide further information, including laboratory values, pertinent imaging, cardiac stress testing, documentation of prior surgery or intervention, medication dosages and schedules, or similar demonstration of effective disease control. Novel conditions or risk factors for hypergravity exposure were reviewed by a panel of Aerospace Medicine board-certified physicians for risk profiling, with specific risks and concerns discussed with relevant subjects approved for inclusion as a part of informed consent. Some examples of inclusion and exclusion criteria are further described in **Table I**.

Predilection toward motion sickness was evaluated on all subjects via the Motion Sickness Susceptibility Questionnaire – Short Form (MSSQ);[8] motion sickness history was not exclusionary. Substantial experience in hypergravity environments (for example, high-performance piloting activities) was considered exclusionary, though prior hypergravity experience if limited (for example, remote one-time prior experiential hypergravity exposure or a prior familiarization flight in high-performance aircraft) was considered acceptable. All participants signed informed consent before taking part in the centrifuge runs.

Equipment and Materials

The NASTAR Center STS-400 high-performance centrifuge is a sustained-G simulator that incorporates a traditional long-arm (arm length = 7.6 m) centrifuge motion base with a gimbaled cockpit module. For the current study, the cockpit module was configured as a generic, single-seat space vehicle with a 120° horizontal × 68° vertical field-of-view with a projected dome display. Audiovisual simulation was provided during each trial by the multimedia system of the centrifuge gondola to enhance the realism of the experience. All subjects were secured in the cockpit with a five-point harness. Monitoring and communication were facilitated using a cockpit-mounted video camera and intercom system. Hemodynamic parameters, including heart rate (HR), respiratory rate, and three-lead cardiac telemetry, were recorded through an integrated hemodynamic monitoring system.

Table I. Examples of Inclusion and Exclusion Criteria for Specific Medical Conditions.

DISEASE CATEGORY	INCLUSION CRITERIA	EXCLUSION CRITERIA
Hypertension	• Baseline systolic >140, <180 mmHg • Baseline diastolic >90, <105 mmHg • Well-controlled on any FDA-approved medication	• Baseline systolic >180 mmHg • Baseline diastolic >105 mmHg • Preflight systolic >200 mmHg
Cardiovascular Disease	• Congenital malformations • Valvular Disease • Dysrhythmias • Coronary Artery Disease • History of acute myocardial infarction • Percutaneous interventions, including stenting • Implanted continuous pacemakers	• Implanted defibrillation devices (AICD) unless fully deactivated • Cardiac transplant • Recurrent defibrillation events [note that a one-time defibrillation followed by intervention (example: ablation) and complete resolution of arrhythmic activity was not considered exclusionary] • Ventricular tachycardia or ventricular fibrillation, if not otherwise related to an underlying or resolved condition • Evidence of unmitigated or reversible cardiac ischemia during any stress testing, severe vascular disease, or similar severe and uncontrolled medical problems identified by any historical documentation or preflight screening • ECG evidence of acute ischemia or malignant dysrhythmia
Diabetes Mellitus	• Type I or Type II diabetes mellitus • Controlled with diet, oral medication, injectable medication, or insulin pump	• "Pre" diabetic with HbA1c < 6.5%, no medications, no lifestyle change [could be included as control subjects (cohort of subjects with no significant medical history)] • HbA1c > 8.0% • Demonstration of poor glucose control (average preprandial baseline blood glucose >250 mg · dL^{-1} • Evidence of advanced disease or sequelae of long-term poor glucose management [e.g., significant or end-stage renal disease (creatinine of >3.0 mg · dL^{-1} or reliance on hemodialysis), autonomic dysfunction, or diabetic retinopathy]

Where inclusion or exclusion criteria were not specified prior to study recruitment, novel conditions or risk factors for hypergravity exposure were reviewed by a panel of Aerospace Medicine-certified physicians for risk profiling.
AICD: automated implantable cardioverter-defibrillator; FDA: U.S. Food and Drug Administration; HbA1c: glycosylated hemoglobin.

Procedures

All subjects were advised to take all regular medication per their usual schedule on the day of participation. Subjects who regularly use antiemetics or vertigo-mitigating medications for prevention of motion sickness symptoms were allowed to do so if desired, provided they reported what medications they used, when they administered the medication, and any side-effects they were experiencing at any time during the study.

Upon arrival at the centrifuge facility, all subjects were asked to review submitted medical history and exam documentation with the medical monitors to ensure that all information was current and accurate. Resting blood pressure (BP), HR, and pulse oximetry (Po_2) were measured at this time. Subjects with significant cardiac histories underwent repeat ECGs for comparison to baseline; identification of new ischemic concern at time of repeat ECG was considered exclusionary. Prior to centrifuge runs, participants were taught a basic anti-G straining maneuver (AGSM) and the "hook" (L-1 closed glottis variant) maneuver. They were advised to use both the muscular strain and hook maneuver during initial $+G_z$ exposure; during subsequent exposures, participants were allowed to determine whether strain or hook maneuver were necessary to mitigate $+G_z$-related symptoms such as grayout or light-headedness. Subjects were asked to report whether muscular strain or hook maneuvers were used and queried on all related symptoms experienced during each $+G_z$ exposure. They were further advised against provocative head movements during centrifuge trials to avoid triggering Coriolis symptoms. Finally, all subjects were oriented to the centrifuge, gondola, and the gondola restraint system prior to each spin.

Approved participants underwent up to five centrifuge profiles in a single day, with each run designed to simulate acceleration profiles anticipated during spaceflight in either a winged or capsule vehicle. Immediately before each profile, subjects received a short description of the acceleration profile of the simulated spaceflight experience followed by a brief practice of the AGSM technique for profiles inclusive of $+G_z$ exposure. Subjects did not receive any stepwise acceleration training or familiarization prior to their initial spaceflight simulation.

The first exposure (Run 1) was designed to simulate a winged vehicle suborbital spaceflight where passengers would be seated upright during launch and supine during re-entry, with sequential $+G_z$ and $+G_x$ exposures on ascent and primarily $+G_x$ exposure on descent (maximum exposure +3.8 G_z and +6.0 G_x). The fourth exposure (Run 4) was similarly designed to simulate a winged vehicle suborbital spaceflight, in this case with an occupant seated upright for both launch and re-entry, resulting in combined simultaneous $+G_x$ and $+G_z$ exposures during descent (maximum exposure +4.0 G_z, +4.5 G_x, 6.1 G resultant). Exposure to each phase of acceleration for winged vehicle profiles did not exceed 2 min and onset rates remained <0.5 G · s^{-1} in the $+G_z$ direction and <1.5 G · s^{-1} in the $+G_x$ direction. The duration of time at the peaks of $+G_x$ and $+G_z$ was <5 s. The combined profile for Run 1 and Run 4 are presented graphically in **Fig. 1**. Audiovisual displays included a simulated field of view of a forward-facing cockpit window. It should be noted that true suborbital flight profiles will include a short period of weightlessness between acceleration peaks that could alter the physiological response but cannot be simulated in a ground-based analog.

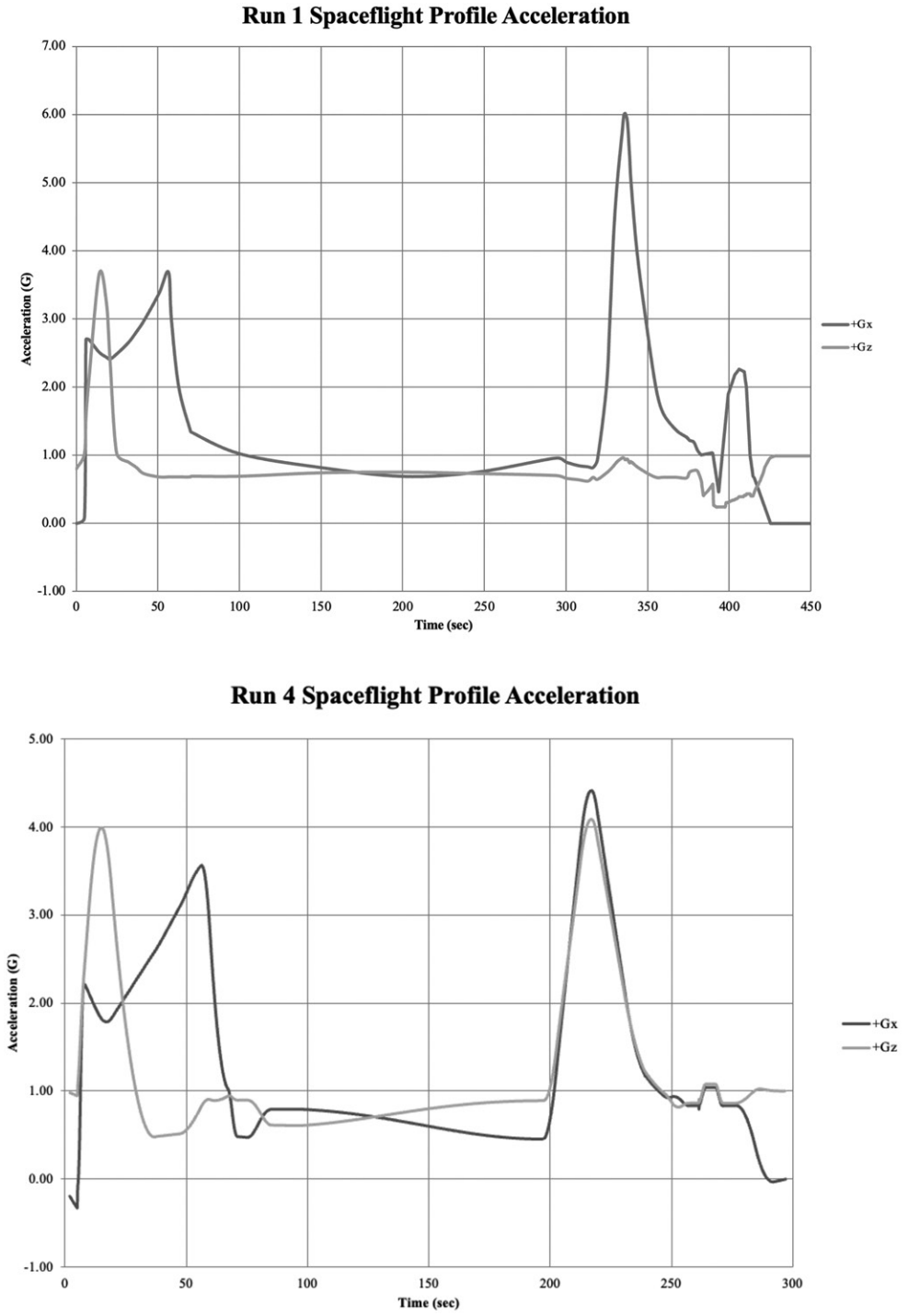

Fig. 1. Winged vehicle profiles. Run 1 was designed to simulate winged vehicle suborbital spaceflight where passengers would be seated upright during launch and supine during re-entry, with sequential $+G_z/+G_x$ exposures on ascent and $+G_x$ exposure on descent (max +3.8 G_z, +6.0 G_x). Run 4 was designed to simulate a winged vehicle suborbital spaceflight with an occupant seated upright for both launch and re-entry, resulting in combined simultaneous $+G_x/+G_z$ during descent (max +4.0 G_z, +4.5 G_x, 6.1 G resultant).

The second centrifuge profile (Run 2) was designed to simulate a nominal capsule launch, where subjects are positioned supine in a capsule launching from a launch pad. The profile was performed through a simulated first-stage main engine cutoff and stage separation; exposure to acceleration was less than 3.5 min and onset rates remained less than $1.5\,G \cdot s^{-1}$ in the $+G_x$ direction only. No $+G_z$ acceleration was experienced in this profile; maximum exposure was +3.2 G_x. The third centrifuge profile (Run 3) was designed to simulate a nominal capsule reentry, descent, and landing, where subjects are positioned supine in an orbiting capsule that subsequently decelerates during descent, followed by deployment of drogue and main

parachutes and, finally, splashdown for a water landing. Acceleration onset was slower but more persistent, with onset rates <0.5 G · s^{-1} in the +G_x direction, and total exposure sustained for approximately 4.5 min with a maximum of +4.2 G_x. Following acceleration related to the descent profile, drogue and main parachute simulation included short transient +G_x exposures of <5 s each. Water landing was similarly simulated by a brief, transient acceleration exposure followed by sinusoidal waveforms representing capsule motion on water. It should be noted that a true capsule reentry profile would be preceded

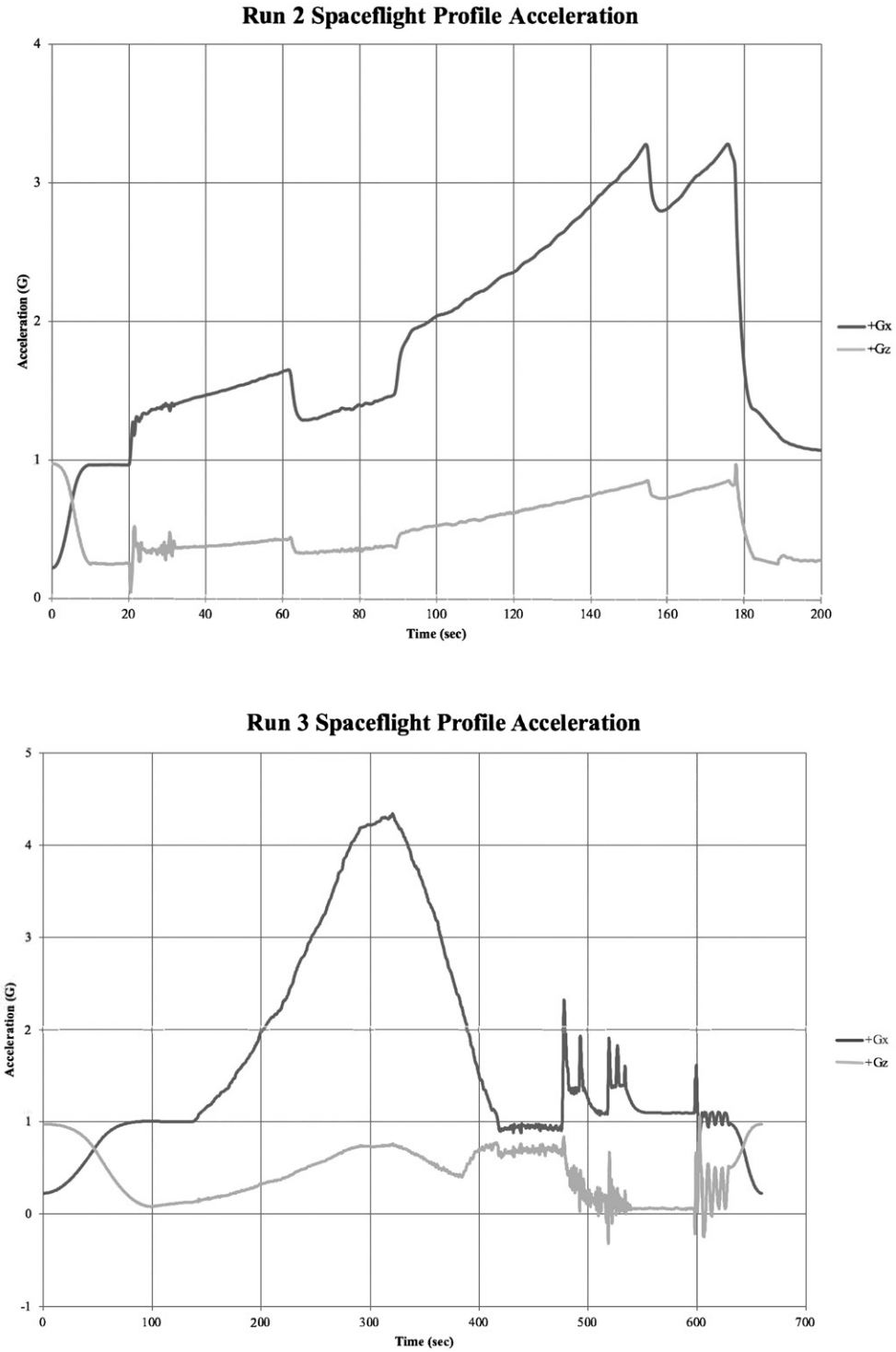

Fig. 2. Capsule vehicle profiles. Run 2 was designed to simulate a nominal capsule launch with supine subjects. Maximum acceleration exposure was +3.2 G_x, with onset rates <1.5 G · s^{-1}. No +G_z acceleration was experienced in this profile. Run 3 was designed to simulate a nominal capsule reentry, descent, and landing, with subjects supine in an orbiting capsule that decelerates during descent, followed by deployment of drogue and main parachutes, and finally, splashdown for a water landing. Maximum acceleration was +4.2 G_x with onset <0.5 G · s^{-1} in the +G_x direction, and total exposure sustained for approximately 4.5 min.

by an on-orbit microgravity period that could contribute to deconditioning and alter physiological response but cannot be simulated in a ground-based analog. Runs 2 and 3 are presented graphically in **Fig. 2**.

The final profile (Run 5) was designed to simulate a capsule launch, similar to Run 2, but in which an abort procedure occurs with activation of a launch escape system (LES). Subjects experience a rapid $+G_x$ acceleration (maximum +3.3 G_x, onset rate $+1\,G \cdot s^{-1}$) during the launch escape followed by a "loft" period of +1 G_x (subjects at rest on their backs) before descent acceleration at a maximum +1.9 G_x (onset rate $<0.5\,G \cdot s^{-1}$). Subjects then experience acceleration exposures representing drogue and main parachute deployment and, finally, a water landing and sinusoidal waveforms representing capsule motion on water. This profile is notably more dynamic, with the accelerations/decelerations described above, and a more noticeable low-amplitude oscillation during descent and drogue and main parachute activation, representative of stabilization rocket firing and swing under parachute. Subjects were additionally exposed to brief, transient $-G_z$ acceleration (maximum −0.74 G_z with sustained $-G_z$ exposure time <1 s) during simulated drogue deployment and landing, similar to expected acceleration profiles of an actual LES abort. Between transient $-G_z$ accelerations, gondola occupants were at rest in supine positioning, but experienced transient head-down accelerations [mean −0.2 G_z (−13°), range 0° to −0.7 G_z (−40°) over a period of ~60 s, time at greater than −3° head down <5 s per acceleration] due to seatback angle and simulated profile events. Run 5 is presented in **Fig. 3**. Capsular profiles (Runs 2, 3, and 5) were inclusive of integrated audio cues, but did not include a visual display; subjects observed a static black starfield on the visual display throughout the profiles.

Subjects were video-monitored at all times in the gondola and subjects and medical monitors were able to access two-way voice communication as needed. Hemodynamic data were monitored during profiles and recorded in real time by medical monitors. HR was recorded at predetermined times before, during, and after each centrifuge run. BP was recorded immediately before and after each centrifuge run. Following each run, subjects were administered data collection questionnaires regarding the occurrence of subjective symptoms (such as chest pain, vertigo, greyout, nausea, and headache, as described in a prior publication[4]) during or after the profiles. After each profile completion, a brief neurovestibular exam was performed including medical monitor visual observations of nystagmus, finger-to-nose coordination, upper extremity motor drift, standing/Romberg, and tandem stand.

At designated times during the day, subjects were administered a series of tasks on a mounted touchscreen tablet in the gondola. Tasks included entering identifiers (subject number, test number) then pressing tablet buttons to recreate a predetermined light pattern as indicated by cue cards available for reference in the gondola; each testing point included two different pattern replication exams. During exams, requesting a repeat of test instructions (e.g., which cue card to reference) was allowed but not expressly offered to subjects

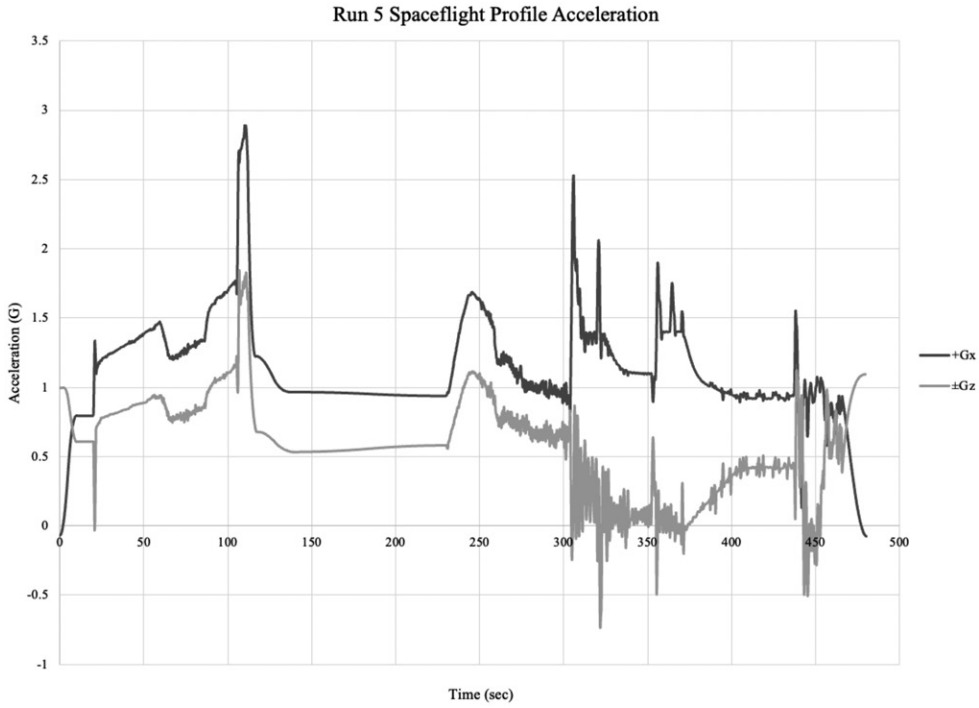

Fig. 3. Abort vehicle profile. Run 5 was designed to simulate a capsule launch with activation of a launch escape system (LES). Subjects experienced a rapid $+G_x$ acceleration (maximum +3.3 G_x, onset rate $+1\,G \cdot s^{-1}$) during the launch escape followed by a "loft" period of +1 G_x before descent acceleration of maximum +1.9 G_x (onset rate $<0.5\,G \cdot s^{-1}$). The loft is followed by transient acceleration (including brief inversion, maximum −0.7 G_z) representing parachute deployment and splashdown, then a sinusoidal waveform representing capsule motion on water.

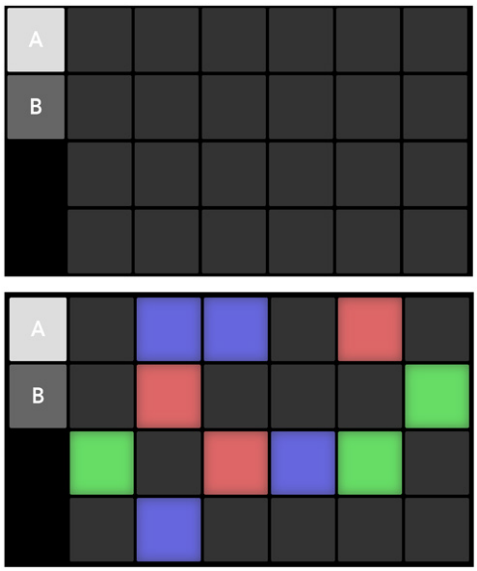

Fig. 4. Tablet lightboard interface. Subjects used a simple touch display to access two testing pages, A and B. On each page, subjects were asked to recreate a lighted pattern while referencing a cue card. Touching each square toggles through alternate colors. Scores were based on both time and accuracy in recreating the referenced cue card pattern.

as an option. Subjects were trained to the tablet lightboard tasks prior to their centrifuge experiences and were able to practice to their comfort level on available tablets in the waiting area prior to any testing and before and between all spins. Tablets independently recorded subject-specific practice effort between testing sessions. Subjects were instructed to treat lightboard tasks as simulated emergency procedures and were informed that they would be scored based on time and accuracy, with the goal of perfect accuracy at the fastest pace possible for completion. All tests were administered with seclusion of subjects (if outside of the gondola) or isolation of audiovisual feeds such that waiting subjects were not privy to test timing or details. An example of the lighted button tablet interface is provided in **Fig. 4**; timing of lightboard tests is provided in **Table II**.

Statistical Analysis

Data analysis followed collection, using descriptive statistics, Student *t*-tests, Chi-squared analysis, Fisher exact, Pearson's correlation, and nonparametric Mann-Whitney U.

RESULTS

A total of 104 subjects were registered for the study during an open recruitment period of approximately 6 mo. Registration website technical issues led to the loss of an unknown number of additional registrants. Of the total registrants, 61 submitted sufficient medical documentation to be considered for the study. There were two subjects who were disqualified due to weight [study maximum was 260 lb (118 kg) due to equipment limitations] and two due to medical reasons [specifically, uncontrolled diabetes with severely elevated glycosylated hemoglobin (HbA1c) and associated disease sequelae]. No subjects were disqualified based on screening ECG. No subjects with novel medical conditions reviewed by the panel were excluded. In four cases, individuals considered by the Aerospace Medicine panel to be higher risk due to their medical history experienced Run 1 at half (50%) intensity to ensure tolerance prior to progressing to subsequent runs and inclusion in the study.

Due to scheduling conflicts, five approved subjects were unable to participate, and two declined to participate due to travel-related financial strain. The remaining 50 subjects were scheduled to participate in centrifuge trials. Of these subjects, four did not participate the day of their trials—one had a personal emergency, one reported an unexpected schedule conflict, one cited COVID-19-related concerns and a desire to limit travel and participation, and one did not provide any reason or notification before failing to arrive for training. There was no significant correlation to sex, age, or medical history in those that failed to arrive for training. The final 46 subjects [31 men (M), 15 women (F)] participated and are included in statistics reported below.

Of the 46 subjects who participated, average age was 37.6 ± 11.5 yr, median age 37 yr, range 19–69 yr. Four participants (three M, one F) had a medical history of Type I diabetes mellitus; six (four M, two F) had hypertension, and nine participants (three M, six F) had significant cardiac history, five of whom (one M, four F) had a history of dysrhythmias including premature ventricular contractions, premature atrial contractions, supraventricular tachycardia, and ventricular tachycardia. There was no significant difference between the ages of subjects with no significant medical history compared to those with reported medical conditions or history, nor was sex distribution significantly different between subjects with no

Table II. Timing and Location of Lightboard Test Administration.

TEST NUMBER	TIME ADMINISTERED	LOCATION
1	Prior to first centrifuge run.	Waiting area
2	At termination of Run 2.	In gondola
3	During Run 3; test deployed during capsule descent and triggered with an audible alarm following peak G exposure, with test onset at +3.6 G_x. Subjects entered identifiers and then were instructed to hold; test was completed after run termination and gondola stop. Deployment time was recorded in addition to accuracy and time to complete test.	In gondola
4	During Run 4; test performed during idle period between launch and landing acceleration phases.	In gondola
5	At termination of Run 5.	In gondola
6	Following completion of all centrifuge experiences.	Waiting area

Subjects were able to access example tests at any time to practice as desired.

significant medical history compared to those with reported medical conditions or history. A total of 15 individuals were required to provide further medical data than minimally required information, including 4 required to provide recent fasting blood glucose trends and HbA1c and 9 required to provide documentation of past cardiac evaluation or intervention.

There was no significant association with prescreening requirements and any hemodynamic alteration or subjective symptoms reported after profiles (such as chest pain, vertigo, greyout, nausea, headache, etc.), and the tolerance or performance of the individuals required to provide more extensive screening was not significantly different from those requiring only minimal screening. There was no significant difference in tolerance of centrifugation or performance during simulated flight based on medical history, pre-existing medical conditions, or medications used. The four individuals considered to be higher risk who experienced Run 1 at 50% prior to further participation included two men with cardiac history and two women with a history of neurovestibular disease associated with high motion sickness predilection. Hemodynamic response in this subgroup to any study profile was not significantly different from the remainder of the study participants. However, three of these subjects chose to reduce the intensity or opt out of one or more profiles later in the day. During study participation, five additional subjects opted out of one or more centrifuge profiles. Subject opt-out of one or more profiles, or voluntary reduction of intensity in one or more profiles, will be collectively termed "subject non-completion" and is further detailed in **Table III**.

There was no significant difference in baseline or test date preparticipation mean arterial pressure or HR based on age, sex, or body mass index (BMI). There was no significant difference in heart rate or respiratory rate response to centrifugation at any phase of flight based on sex or BMI. Older individuals (>50 yr) demonstrated less HR elevation at $+G_z$ exposures and during the simulated LES $+G_x$ acceleration experienced in Run 5 (HR Run 1 peak $+G_z$: <50 yr = 149.1 ± 19.0 bpm; ≥50 yr = 124.3 ± 25.7 bpm, df = 44, $P = 0.006$; HR Run 4 peak $+G_z$: <50 yr = 138.3 ± 22.4 bpm; ≥50 yr = 107.7 ± 33.0 bpm, df = 41, $P = 0.006$; HR Run 4 peak resultant: <50 yr = 134.0 ± 22.8 bpm; ≥50 yr = 101.0 ± 29.9 bpm, df = 41, $P = 0.003$; HR Run 5 LES: <50 yr = 97.8 ± 15.2 bpm; ≥50 yr = 79.5 ± 17.1 bpm, df = 37, $P = 0.01$). This was not correlated to any difference in subjective symptoms reported by the subjects. There was no significant association between any baseline or test date BP or HR and subject noncompletion. There were no episodes of near or complete G-induced loss of consciousness (A-LOC or G-LOC) during any centrifuge exposure. There was no association between reported past medical or psychological history and subject tolerance, subjective symptoms, or risk of subject noncompletion.

Nausea or stomach awareness was a common complaint by subjects: 12 subjects (26.1%) reported nausea during or after 1 or more centrifuge runs, and 6 subjects (13.0%) reported sufficient nausea to prompt withdrawal and noncompletion. One subject vomited after completion of Run 1 and opted out of any further profiles (see Table III); no other subjects reported emesis. In three cases of subject noncompletion, subjects complained of absent or discordant visual cues during capsule runs, particularly during rapid reorientation of the gondola (for example, during simulated parachute deployment and subsequent deceleration or at the termination of a profile), as contributing to their discomfort and reported decreased or nonexistent symptoms during winged vehicle profiles inclusive of integrated visual displays. However, there was no statistical difference in the frequency of nausea reported across all subjects in winged vs. capsule postprofile questionnaires. Frequency of symptoms reported on postrun questionnaires were not associated with subject noncompletion. There was no association between preparticipation MSSQ score and postrun reported nausea or risk of noncompletion. No subject chose to premedicate with antinausea medications on the day of centrifuge participation; one subject ingested crystalized ginger after Run 4, noting stomach awareness, then completed Run 5 with mild nausea reported on postrun questionnaires (improved from moderate nausea reported on Run 4 questionnaires). Three subjects took a single dose of ondansetron oral dissolving tablets after terminating their participation in the study but did not otherwise medicate during spins. No other use of antiemetics was reported.

Subjects demonstrated variable neurovestibular response following the profiles. Nystagmus was particularly notable after

Table III. Subject Noncompletion by Medical History and Rationale for Noncompletion, as Offered by the Subject.

SUBJECT MEDICAL HISTORY	SCREENED VIA 50% PROFILE	EARLY TERMINATION	REDUCED INTENSITY	SUBJECT RATIONALE
Control	No	Yes – Run 3	No	Motion sickness / discordant visuals
Control	No	Yes – Run 3	No	Motion sickness
Lung (asthma)	No	Yes – Run 3	No	Motion sickness
Cardiac (dysrhythmia)	No	Yes – Run 3	No	Motion sickness / discordant visuals
Diabetes (insulin-dependent)	No	Yes – Run 3	No	Motion sickness / discordant visuals
Neurovestibular	Yes	Yes – Run 1	No	Motion sickness / vomiting
Cardiac (structural disease)	Yes	Yes – Run 5	No	Chest discomfort ($+G_x$)
Neurovestibular	Yes	No	Yes – Run 4 completed at 50% intensity	Expressed concern for potential vertigo or motion sickness symptoms if full-strength profile pursued

Three of the subjects that ultimately did not complete all study objectives were identified prior to participation as potentially high risk and were required to experience Run 1 at 50% intensity prior to study participation.

Run 1 (58.7% of subjects), then diminished in cohort prevalence after subsequent profiles (Run 2: 45.5%; Run 3: 40.5%; Run 4: 36.1%; Run 5: 29.4%). Individual subjects demonstrated more variability in nystagmus findings. Of the subjects demonstrating nystagmus at any time during the centrifuge experience, the majority (64.9%) of subjects experienced stable or diminishing nystagmus in subsequent profiles while a smaller cohort (35.1%) demonstrated increasing or variably present nystagmus (for example, nystagmus in two nonconsecutive profiles but absent in others). In these variable nystagmus subjects, there was no correlation between any specific profile or profile type and the identification of nystagmus in postprofile evaluations. Difficulty with a standing/Romberg test was noted after Run 1 in 56.5% of subjects; this similarly diminished (in cohort prevalence and as a subject-specific finding) after subsequent profiles (Runs 2–4: 35–37% of subjects, Run 5: 20.6%). There was no significant difference in objective neurovestibular findings after profiles between those who completed all profiles and those who opted out of one or more profiles.

Subjects generally reported feeling comfortable with the lightboard and all subjects reported feeling that they had adequate time for training and practice prior to any examinations. Though lightboards remained available throughout the day, most subjects did not continue to practice between testing events: after Test 1, 14 subjects (30.4%) chose to practice prior to further tests; after Test 2, 3 subjects (6.5%) practiced; and after Test 3, 4 subjects (8.7%) practiced. No subjects chose to practice after the fourth test. There was no association between number of practice tests, or practice between tests, and performance (time or accuracy). Average time to complete the tests was linearly associated with age, with younger individuals completing the test faster than older individuals [time range 8.7–32.8 s; quartiles 10.8 s, 13.3 s, 16.2 s; $r(44) = 0.66$, $P < 0.001$; by age, 19–29 yr average test completion time = 12.1 s, 30–49 yr = 13.4 s, ≥50 yr = 21.9 s]. However, when comparing performance to each subject's baseline (Test 1), there was no association between age and delta time to complete any test (compared to precentrifuge baseline). Similarly, time to deploy the lightboard while under acceleration (Test 3) was linearly associated with age, with younger subjects accessing the lightboard faster than older [time range 10–38 s, quartiles 13 s, 15 s, 18 s, $r(35) = 0.52$, $P = 0.001$]. Deployment time was not associated with performance. There was no association between any time metric or accuracy and sex. One subject reported cold hands in the gondola and noted difficulty activating the touchscreen as a result; however, that subject's test completion time was not significantly different from the remainder of the subjects. There was no noted difference in lightboard performance between individuals with varied medical history.

In total, five subjects (10.9%) completed all six examinations without error. Eight subjects referenced the wrong cue card on at least one test; four of these subjects referenced the wrong cue card on multiple tests. Two individuals entered an incorrect test identifier (which registers both cue-card light patterns incorrectly) at one test event; one of these subjects also entered the wrong subject identifier at a different test event (though the test was otherwise performed without error). There was no association between sex or age and the use of the wrong cue card or identifier. However, overall test accuracy was linearly associated with age, with younger persons having better accuracy than older [average error by subject: range 0–4.6 errors, quartiles 0.08, 0.17, 0.33 errors; $r(44) = 0.36$, $P = 0.006$; by age, 19–29 yr average errors per test = 0.4, 30–49 yr = 0.4, ≥50 yr = 1.3 errors]. Excluding incorrectly referenced cue cards, subjects averaged a cumulative 1.7 ± 1.7 errors across all tests. When considering the 12 distinct exams given to each subject (each test point with two lightboard exams; exams not completed by subjects terminating a profile were excluded), subjects completed 87.6% of all exams without error. Across all test events, 11 subjects (23.9%) requested repeat of instructions; requesting repetition had no significant effect on completion time or accuracy.

Accuracy was equivocal across tests with the exception of Test 3, in which subjects performed significantly better compared to other testing points, with 1 subject making 2 errors and the remaining 39 subjects completing the test without error. There was no other difference between performance on any of the other five tests, nor was there any other significant difference between performance on tests in the gondola compared to those performed in the waiting area prior to any centrifuge experience.

DISCUSSION

This study expanded upon current knowledge of layperson performance in hypergravity environments, but additionally incorporated capsule-style profiles to increase applicability of findings to the broader commercial spaceflight industry. Overall, subjects performed well during centrifuge experiences despite varied past medical history and pre-existing medical conditions. No clinically significant or symptomatic cardiac, cerebrovascular, hyper- or hypoglycemic, or respiratory events occurred during the study, and there were no adverse events associated with the use of any medication for any pre-existing condition. Similar to prior studies,[2,4,13] prescreening requirements were generally felt to be effective in identifying subjects likely to tolerate simulated spaceflight experiences. Even so, it is worth noting that this study demonstrated an increased frequency of subject noncompletion compared to prior studies.

Prior studies have reported between 3–7% of subject noncompletion after similar screening, training, and centrifuge profiles;[2,4,5] this study resulted in 17.4% subject noncompletion. Prior studies report 5–20% of subjects complaining of nausea during one or more profiles; here, 26.1% of subjects reported nausea symptoms during their experience. One prior study in particular demonstrated no correlation between subject noncompletion and length of training;[2,14] similarly, we suspect that the increased rate of subject loss was unlikely to be related to the omission of stepwise training, low-intensity, or single-vector familiarization exposures prior to simulated spaceflight. In this study, many of the subjects opting out of the full experience

cited absent or discordant visual cues during capsule runs as contributing to nausea and discomfort and often prompting their withdrawal from further centrifugation. Prior reports in centrifuge and other simulation and virtual reality environments have highlighted the benefit of well-aligned visual cues in reducing nauseogenic stimuli associated with centrifuge motion[1,11] and absent visual stimuli, or poor alignment of stimuli with concurrent subject motion, resulting in nausea or related symptoms.[6,16] Discordant visual cues (specifically, the static starfield display that did not shift with gondola motion in capsule profiles) likely contributed to discomfort and the higher frequency of subject noncompletion. Further, there was no correlation between history of motion sickness in noncentrifuge environments and subject noncompletion; history of vehicular motion sickness is often not predictive of centrifuge simulator sickness attributed to vestibulo-ocular conflict.[16] Prior studies of similar protocols and profiles have reported a positive correlation between high MSSQ score (reported history of motion sickness predilection) and study noncompletion;[14] this was not observed in the present study.

Interestingly, subject reports of nausea following centrifuge exposures did not correlate with type of profile (winged vs. capsule). In retrospect, subjects frequently reported that they had experienced onset of nausea or related symptoms initially during capsule profiles, but then symptoms had persisted or progressed, leading to continued reporting of nausea or other motion sickness symptoms during subsequent profiles, including the second winged profile (Run 4). As such, statistical correlation between motion sickness and type of profile may have been biased by the prescribed order of profiles over the course of the training program or may be attributable to cumulative and progressive symptoms associated with repetitive centrifugation. Similarly, reports of nausea following profiles did not correlate with subject noncompletion, even when subjects retrospectively reported nausea as contributing to their decision to opt out of additional profiles. This suggests that subjects may have lacked awareness of developing symptoms, or potentially chose to hide or minimize symptoms of motion sickness. Alternatively, it is possible that nausea onset was rapid enough and unique to the profile prompting noncompletion that symptoms were not indicated on preceding postspin questionnaires. Any delay in completing questionnaires after termination of participation (for example, a delay due to subject nausea or other discomfort) may have led to reporting bias or minimization of symptoms on forms completed after those symptoms had improved. Finally, it is notable that prevalence of neurovestibular symptoms (nystagmus, imbalance) diminished over the day and was not significantly associated with reported nausea or subject noncompletion. The literature regarding the correlation of neurovestibular imbalance with simulator sickness is variable and often conflicting, but prior studies have often found no direct correlation between nausea or discomfort associated with simulator sickness or vestibulo-ocular conflict and demonstrable neurovestibular impact.[9,10]

Lightboard performance was age-dependent, with younger subjects demonstrating slightly faster completion times, faster deployment in hypergravity conditions, and slightly improved accuracy compared to older subjects. This may be secondary to age-related factors such as visual accommodation and reaction time. However, it is worth noting that delta performance compared to subject baseline was consistent across age groups. Further, 87.6% of all exams were completed without error, including many completed by older subjects, and frequency of practice was not significantly associated with performance. Ultimately this likely suggests that the test was easy to master, even with limited training time or practice effort. Ideally, emergency spaceflight actions (particularly those which an SFP may be asked to complete) should be similarly easy to master and perform even in stressful circumstances. Further, while a true spaceflight emergency would likely have more operational impact, hypergravity as a stressor did not appear to significantly degrade performance.

Most subjects chose to practice only minimally on the lightboard, despite the ubiquitous presence of the lightboards in the waiting area. Indeed, those subjects who professed to being driven by a competitive spirit, or most expressive of anxiety regarding their performance on the examinations, were the subjects most frequently practicing on the lightboards between exams. Anecdotally, a competitive spirit appeared to be a more effective motivator in subjects than simple encouragement to perform to the best of their own ability or any investigator-driven effort to focus or motivate participants. Some subject groups engaged in impromptu competition, requesting their lightboard exam results and comparing with others in their group; these individuals frequently practiced and performed with high accuracy and increasing speed during examination points. With these exceptions, subjects generally demonstrated low motivation to continue practicing throughout the day. Similarly, simple encouragement may not be sufficient to motivate SFPs to practice actions or protocols for use only in emergency situations. Ideally SFPs would recognize the need for careful practice of all emergency actions; in reality, it is quite possible that effort will be limited to the minimum required prior to flight.

Low-intensity lighting in the gondola, particularly during capsule profiles, rendered lightboard colors somewhat more difficult to distinguish, with subjects reporting occasional reliance on alternative cues (for example, counting grid blocks) for pattern recreation. It is not unlikely that vehicular lighting may similarly impact display readability in space vehicles; this highlights the need for testing of all visual displays or user interfaces in all potential lighting scenarios (low light, smoke-filled cabin) and with all potential visual impairments. While a colorblind alternative test was available, it was not requested by any subject in this study; however, such considerations are necessary to fully accommodate layperson populations engaging in spaceflight activities.

The simulated emergency and lightboard actions in this study protocol were intended to provide a higher-fidelity representation of actual operational activities in an emergency compared to those simulated in prior studies of this

kind. Even so, it is worth noting that prior emergency scenarios similarly demonstrated frequent errors and difficulty with multistep operational actions.[2,3] Further, the prior study reported 5% of subjects requesting repetition of instructions to ensure their actions were correct; here, 23.9% of subjects requested repetition. Importantly, the majority of subjects in both studies did not request repetition or confirmation of appropriate actions. Coupled with the frequency of error, this highlights the likelihood of mistakes and the low likelihood that layperson SFPs will independently think to cross-check their actions to prevent error in a real operational emergency.

The frequency of wrong cue card and wrong identifier entries represent the potential for catastrophic failure in an operational environment. While this is a simple mistake in a simulation, if an SFP were to follow an incorrect protocol or take operational actions in error during an emergency response to a spaceflight contingency, such actions could potentially result in loss of crew life. The high frequency of such errors, made by 10 subjects (21.7% of participants) in 1 or more exams, should raise awareness of the potential for SFPs to make errors in real-time emergency operational scenarios. Verbal instructions and multistep procedures may contribute to such risk; simple procedures with binary decision points, directed actions, and feedback to confirm actions taken may improve upon layperson performance in emergencies. Finally, while 87.6% of exams were without error, it is worth noting that 12.4% of exams, therefore, included error. Even small errors in a contingency or emergency response protocol could have catastrophic consequences. Errors should be expected in layperson SFP operational activities, regardless of practice or preflight proficiency. Further, simulated emergency actions will never fully recreate emergency conditions, and actual performance should be expected to be worse in a true emergency scenario.

This study enhances the available literature basis for understanding of layperson tolerance in commercial spaceflight analog conditions. The inclusion of capsular profiles broadens the applicability of findings to multiple vehicle designs and provides additional understanding of layperson responses to variable hypergravity environments. In general, this study identified an increased frequency of motion sickness compared to prior studies, though this finding may be attributable to discordant centrifuge visual displays, and an overall higher frequency of subject noncompletion compared to prior literature. Even so, most individuals with well-controlled medical disease appear to be physiologically capable of tolerating the hypergravity stressors of suborbital and orbital spaceflight. The frequency of task errors in this study highlights the potential for mistakes in operational activities when performed by laypersons. While mistakes represent a low-risk event in an analog simulation environment, similar errors in an operational environment could be catastrophic. These findings highlight the need for further study to determine the best approach to training, procedural design, and simplicity of actions to best accommodate the capabilities of layperson participants in a critical operational environment.

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