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RESEARCH ARTICLE

Virtual reality as a countermeasure for astronaut motion sickness during simulated post-flight water landings

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Abstract

Entry motion sickness (EMS) affects crewmembers upon return to Earth following extended adaptation to microgravity. Anticholinergic pharmaceuticals (e.g., Meclizine) are often taken prior to landing; however, they have operationally adverse side effects (e.g., drowsiness). There is a need to develop non-pharmaceutical countermeasures to EMS. We assessed the efficacy of a technological countermeasure providing external visual cues following splashdown, where otherwise only nauseogenic internal cabin visual references are available. Our countermeasure provided motion-congruent visual cues of an Earth-fixed scene in virtual reality, which was compared to a control condition with a head-fixed fixation point in virtual reality in a between-subject design with 15 subjects in each group. We tested the countermeasure's effectiveness at mitigating motion sickness symptoms at the end of a ground-based reentry analog: approximately 1 h of 2Gx centrifugation followed by up to 1 h of wave-like motion. Secondarily, we explored differences in vestibular-mediated balance performance between the two conditions. While Motion Sickness Questionnaire outcomes did not differ detectably between groups, we found significantly better survival rates (with dropout dictated by reporting moderate nausea consecutively over 2 min) in the visual countermeasure group than the control group (79% survival vs. 33%, $t(14) = 2.50$, $p = 0.027$). Following the reentry analogs, subjects demonstrated significantly higher sway prior to recovery ($p = 0.0004$), which did not differ between control and countermeasure groups. These results imply that providing motion-congruent visual cues may be an effective mean for curbing the development of moderate nausea and increasing comfort following future space missions.

Keywords Vestibular · Adaptation · Centrifugation · Sensory conflict · Space motion sickness · Entry motion sickness

Introduction

Significance of spaceflight driven motion sickness

The emergence of deep space mission objectives and commercial flights to low Earth orbit have sparked a renewed concern with crew motion sickness resulting from spaceflight gravity transitions. Most commonly characterized by varied symptomology resulting from real or apparent motion

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(Lackner 2014), motion sickness may manifest in humans as severe discomfort, repeated bouts of vomiting, and even prolonged incapacitation when venturing to and from space (Lackner and DiZio 2006; Thornton and Bonato 2013).

Historically affecting 60–80% of astronauts (Heer and Paloski 2006), 'space motion sickness' (SMS) (also referred to as space adaptation syndrome) occurs upon transitioning to a microgravity environment from Earth gravity. This mode of motion sickness is thought to arise due to a modified gravitational stimulus, resulting in persistent unexpected sensory cues from graviceptors, particularly the otoliths (Lackner and Graybiel 1987). This explanation of SMS is consistent with sensory conflict theory of motion sickness in general (i.e., the difference between the peripherally 'sensed' and centrally 'expected' vestibular cues) (Oman 1982, 1990; Reason and Brand 1975), and neural correlates of sensory conflict have been observed in the brainstem and cerebellum (Oman and Cullen 2014).

The sensory conflict experienced in space is theorized to drive adaptation through reinterpretation of the internal model used to process sensory cues (Allred et al. 2023; Kravets et al. 2021) and reweighting of different sensory modalities. Evidence for reweighting has been previously observed in functional MRIs of astronauts and cosmonauts after returning from orbit (Hupfeld et al. 2022; Pechenkova et al. 2019) wherein brain regions associated with visual, somatosensory, proprioceptive, and vestibular sensing change in terms of activation or functional connection when comparing pre- to post-flight values. This conflict-driven adaptation also occurs when returning to Earth from microgravity where crewmembers experience motion sickness during readaptation to Earth 1 g (Gorgiladze and Brianov 1989). Coined 'entry motion sickness (EMS)', symptoms arising from this mode of motion sickness are likely to be exacerbated by the passive motions experienced by the crew during splashdowns (specifically with the utilization of the SpaceX Dragon and NASA Orion capsules).

Because SMS and EMS pose significant operational and performance decrements to crewmembers in the first days following a gravity transition (Ortega et al. 2019), effective countermeasures to these modes of motion sickness must be developed to improve crew health and performance during future NASA exploration class missions. Such countermeasures may also be leveraged to provide more tolerable experiences for commercial space travelers.

Existing countermeasures

Currently, pharmaceutical countermeasures such as the administration of promethazine or scopolamine are utilized with varying degrees of success (Bagian 1991; Bagian and Ward 1994; Davis et al. 1993a, b; Davis et al. 1993a, b; Graybiel and Lackner 1987) to either prevent, delay, or ameliorate motion sickness symptoms following gravity transitions (Lackner and DiZio 2006). Due to the delay in effectiveness of orally administered drugs after the onset of motion sickness symptoms, these drugs can also be administered parenterally; promethazine can be injected (Davis et al. 1993a, b) and intranasal scopolamine is currently in development (Beltran et al. 2022). The most commonly administered post-flight treatment, meclizine, is often taken prophylactically before landing (Lee et al. 2020).

However, many anticholinergic pharmaceutics have unwanted side-effects including drowsiness and operational performance degradation (Cowings et al. 2000; Lucot 1998; Wood et al. 1990) at current dosages and occur following administration, during which mission critical operational tasks (e.g., vehicle egress) are typically necessary. Additionally, pharmaceutical shelf-life and long-term stability may prove inadequate for long-duration deep-space missions.

Given the limitations of these countermeasures, there exists a need to develop non-pharmaceutical, or even technological, countermeasures to SMS and EMS. In the terrestrial environment, existing works have found motion sickness symptoms to be affected by non-pharmaceutical stimuli, which may provide avenues of preventing or attenuating symptoms. Looking out the window effectively reduces carsickness (Griffin and Newman 2004; Perrin et al. 2013; Schmidt et al. 2020; Turner 1999), and sailors have historically relied on going on deck and viewing the horizon to ameliorate seasickness (Gupta et al. 2021; Stoffregen et al. 2013).

In studying seasickness using a ship motion simulator, motion sickness was found to be alleviated by providing subjects with an Earth-fixed visual scene, with increasing sickness symptoms observed in the no visual cues (blindfolded in the dark) and inside cabin-view conditions, respectively (Bos et al. 2005). Further, apparent motion driven by visual sensory information that is incongruent with actual motion is known to induce motion sickness (this mode of motion sickness is alternatively referred to as simulator or cybersickness) (Bos et al. 2022; Davis et al. 2014; Kennedy et al. 1993). Together, these findings indicate the nauseogenic nature of incongruent visual and vestibular cueing. This aligns with sensory conflict theory predictions that visual sensory information modifies the central expectation of vestibular cues, and thus incongruent cross-sensory information will lead to sensory conflict driven motion sickness. Sensory conflict theory provides insight into potential avenues for the attenuation of nausea from motion sickness by providing a motion-congruent visual scene. Specifically, that visual cues could help modify the centrally expected vestibular measurements, such that the central expectation more closely matches reality. This could result in less motion sickness-inducing conflict with the peripherally sensed vestibular measurements.

Apart from this modulation, reliable, motion-congruent visual cues may result in more rapid centrally driven vestibular adaptation following a modification of vestibular information (Héroux et al. 2015) (e.g., following a gravity transition). Because the maladapted state is partially responsible for the onset and development of motion sickness (in conjunction with passively experienced motions), expediting (re)adaptation may contribute to motion sickness mitigation.

Currently, neither natural nor virtual external visual cues are available to crewmembers in the capsule environment during and following splashdown, and visual information is restricted to an unhelpful inside cabin-view, which provides cues in conflict with a natural outside view. Based on our current understanding of how visual cues impact the onset and development of motion sickness symptoms, we hypothesize that EMS symptoms will be reduced by administering an Earth-fixed (i.e., motion-congruent) visual scene to crewmembers prior to capsule egress.

Objectives

This study aims to quantify the efficacy of providing visual cues of self-motion for individuals experiencing wave-like motion following a gravity transition in order to reduce motion sickness incidence and severity and mitigate sensorimotor impairment. Primarily, we hypothesized that—when preceded by a gravity transition paradigm (approximately 1 h in duration)—the administration of a motion-congruent, Earth-fixed virtual visual scene during a capsule wave-like motion paradigm would result in less severe motion sickness symptoms compared to a control condition (a head-fixed visual fixation point). Secondarily, we hypothesized that, following the wave-like motion paradigm, the visual scene condition would result in better vestibular-mediated balance performance compared to the control condition.

Methods

Astronauts returning from microgravity undergo a gravity transition followed by sea state motion during water landings. To simulate this experience, we employed ground-based analogs. In summary, our Human Eccentric Rotator Device (HERD, Fig. 1a) was used to simulate gravity transitions using the Sickness Induced by Centrifugation (SIC) paradigm, and wave-like motion was simulated using the Tilt Translation Sled (TTS, Fig. 1b). Both motion devices are located at the University of Colorado, Boulder. The Meta Quest 2 virtual reality (VR) headset was used to provide visual cues congruent with the wave-like motion. The scenes displayed on the headset were developed and controlled with the Unity game-engine development platform.

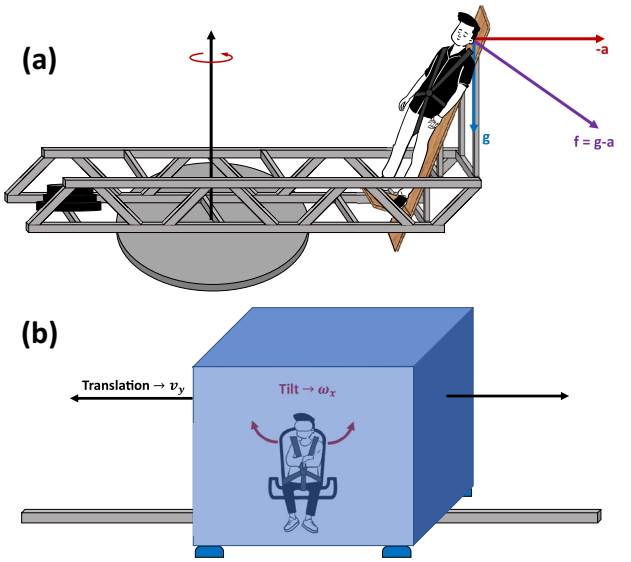

Fig. 1 **a** Human Eccentric Rotator Device (HERD). **b** Tilt-Translation Sled (TTS)

During and after the wave-like motion, motion sickness symptoms and anxiety progression were recorded through subjective verbal reporting. Standing balance before centrifugation, immediately after the wave-like motion, and following recovery was assessed using modified Romberg balance testing and an inertial measurement unit (IMU).

Sickness induced by centrifugation paradigm

The SIC paradigm posits that prolonged exposure to hypergravity using centrifugation is effective at replicating symptoms of space motion sickness as well as postural instabilities and gait destabilization (Albery and Martin 1996; Bles et al. 1996, 1997; Bles and de Graaf 1993; Groen et al. 1996; Nooij et al. 2005, 2007, 2008; Nooij and Bos 2007; Ockels et al. 1990). The severity of symptoms and the recovery time are dependent on the force and duration of centrifugation as characterized by Nooij and Bos, 2007. Because centrifugation during the SIC paradigm is thought to induce a reinterpretation of sensory cues from the graviceptors in the presence of a modified net gravito-inertial force, SIC represents an effective existing ground-based analog for simulating motion sickness and sensorimotor impairment following a gravity transition. SIC has been used extensively to replicate the transition from 1G on Earth to 0G in orbit (Albery and Martin 1996; Bles et al. 1997; Groen et al. 1996; Nooij et al. 2005, 2007; Nooij and Bos 2007; Ockels et al. 1990). To date, there has been no study mapping duration of spaceflight to SIC duration in terms of EMS symptoms.

The HERD is a short-radius centrifuge (9 feet, or 2.74 m) shown in Fig. 1a. One arm of the HERD centrifuge has a "bed" tilted outward 30 degrees from the vertical such that

subjects experience 2G hyper-gravity in the head-centered negative x-direction (i.e., "eyeballs in"). Subjects are secured to the padded "bed" using a five-point harness and shoulder supports, and a headrest. The headrest has thick cushioning on both sides of the subject's head to dissuade roll, pitch, and yaw head rotations, preventing the Coriolis cross-coupling illusion during centrifugation (Bretl et al. 2019; Bretl and Clark 2020, 2022). The test was performed in the dark with the subject's eyes closed to prevent dizziness due to any light leaking into the room. The foot plate of the HERD was adjusted such that the radius of the subject's head was at 104 in (2.64 m) and a rotation rate of 24 RPM could be used to generate 2Gx at the subject's eyes for each participant. Spin-up occurred incrementally such that subjects could comfortably adjust to different levels of centrifugation prior to reaching 2Gx. Due to the changing direction of the gravito-inertial force (GIF, or $\boldsymbol{f}$) vector from Earth-vertical to 2Gx, and the bed's mostly upright, fixed position, subjects reliably noted the sensation of falling/pitch tilting backwards as they spun up. Hand holds were provided to mitigate the perceived instability caused by this sensation.

Subjects were exposed to 2Gx on the HERD for 56 min plus spin-up and spin-down time. On average, spin-up took a total of six minutes and spin-down took two minutes. This hyper-gravity exposure was expected to generate mild to moderate SIC symptoms (when followed by head motions) according to Nooij and Bos, 2007, who tested the effects of SIC at 2Gx for 45 min and 90 min. Immediately following SIC on the HERD, subjects were transferred to the TTS via a wheelchair with their head restrained to avoid provocative head tilts during transit.

Wave-like motion

Subjects were exposed to wave-like motion using the TTS for up to an hour. The TTS is a motion device that can perform roll tilt and lateral (i.e., Earth-horizontal) translation along a linear track (Fig. 1b). We developed a wave-like motion profile by analyzing the energy spectra of Coastal Data Information Program (CDIP) Station 067—a buoy located roughly 65 miles off the coast of Southern California and a candidate site for future Orion capsule recoveries. To capture the expected sea-state during recovery, buoy data was extracted during NASA's Underway Recovery Test-7. Significant wave height during the test was 1.02 m on average which is a three on the WMO Sea State Code, or a slight sea state.

Energy density data from the buoy during a 12-h window beginning at 1100 UTC on October 31, 2018 was parsed for every half hour and summated. This summation was then converted into a cumulative density function by normalizing it by the maximum energy amplitude, and ten frequencies and their corresponding normalized amplitudes were randomly selected using this distribution (range: 0.055–0.23 Hz) to generate roll-tilt and lateral translation sum-of-sines profiles. Incorporating the semi-coupled nature of waves, eight of these frequencies were used for the translation profile while two additional frequencies were randomly selected to be used for tilt. A random phase-shift was also used with each wave to mimic the randomness of the ocean sea state. The maximum tilt amplitude was scaled to 5 degrees and the maximum translation was scaled to 0.75 m. These values were selected after exploratory pilot testing found them to sufficient to produce motion sickness to varying degrees across individuals. Finally, four-second ramp up and ramp down profiles were added by using an 8^{th} order polynomial spline to fit the profiles to initial zero-values for position, velocity, and acceleration. The profiles were set to be 15 min long and were repeated four times to accomplish a full hour of motion.

Subjects were strapped into the TTS using a five-point harness, and an adjustable head restraint was employed to secure subjects' heads. Subjects underwent wave-like motion for up to an hour (dependent on stopping criteria, discussed below), followed by another hour of recovery sitting with eyes open on a stool in an illuminated lab space. Two-way audio communication was available between the subject and operators during both the HERD and TTS protocols. Further, the subject was monitored via an infrared camera and both subject and operators were provided with buttons to halt motion.

Independent variables

To quantify the efficacy of visual cues at mitigating motion sickness, a between-subject experimental design was implemented with two experimental groups: a visual countermeasure group and a control group. The visual countermeasure group had congruent visual cues of Earth-fixed motion available during the wave-like motion paradigm while the control group was provided with a head-fixed visual fixation point. Both scenes were displayed using the Meta Quest 2 VR headset. The visual countermeasure scene consisted of a forested area with trees for rich references of verticality and people to help provide an approximate reference of scale for perceiving lateral linear translation. The scene moved opposite the direction of subject movement, generating veridical cues of self-motion (e.g., as the subject tilted 5 degrees, the VR scene tilted 5 degrees in the opposite direction from the subject's perspective, as it would in a naturalistic visual scene). Examples of this scene and the result of subject movement are shown in Fig. 2. The control scene consisted of a black background with a white fixation point. The fixation point did not move across the display, regardless of subject motion.

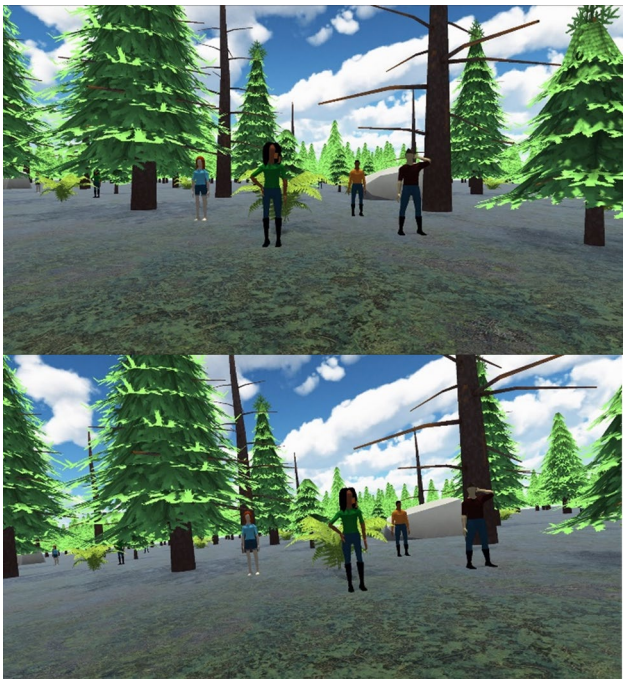

Fig. 2 Visual countermeasure forest scene. Top image demonstrates scene at rest and bottom image shows how the scene would change following the subject translating leftward and tilting in a clockwise (right ear down) roll

The headset brightness was fixed regardless of experimental group. Subjects were instructed to size the headset comfortably for themselves. Interpupillary distance (IPD) was measured using either EyeMeasure (iOS) or GlassesOn (Android), and then set to the closest value available on the Quest 2.

Dependent variables

Subjective data consisting of motion sickness and anxiety scoring was the primary metric collected during this study. Motion sickness scores were collected using a Motion Sickness Questionnaire (MSQ) (Kennedy et al. 1993; B. D. Lawson 2014a, b) every five minutes during and after wave-like motion. The full MSQ consists of 28 symptoms associated with motion sickness and asks the subject to rate each symptom on a scale of 'none', 'slight', 'moderate', and 'severe'. An ordinal score was derived from these ratings by converting them to a scale of 0–3 respectively and summing the values for all symptoms at each time point. Thus, the lowest level of motion sickness on the scale is 0, while higher numbers correspond to more severe motion sickness. In theory, this results in a maximum score of 84; however, the antithetical nature of many of the symptoms (e.g., "increased appetite?" and "decreased appetite?") makes it unlikely that this could ever be achieved. To avoid confusion in the interpretation of the symptom definitions, subjects were asked if they required clarification on any of the 28 MSQ symptom definitions prior to the experiment and were given definitions consistent with B. D. Lawson 2014a, b supplemented with Oxford Languages 2022 (Oxford Languages was used for symptom definitions not explicitly defined by Lawson). The rating scale itself was entirely subjective.

To further investigate particular symptoms within the MSQ, we considered grouping questions in categories. Cha et al 2021 sorted the symptoms of the MSQ into six categories: gastrointestinal disturbance, thermoregulatory disruption, alterations in arousal, dizziness/vertigo, ocular, and general (Cha et al. 2021). Being of specific interest to this study, we divided the MSQ scores into subcategories based on gastrointestinal disturbance (GI), alterations in arousal (sopite), and ocular symptoms.

GI disturbance includes symptoms such as stomach awareness, increased or decreased appetite, nausea, and vomiting. It represents the classical symptoms that people most often associate with motion sickness. Sopite syndrome is a response to motion sickness that is categorized by apathy, lethargy, and the inability to concentrate (Graybiel and Knepton 1976; Lawson and Mead 1998). However, sopite symptoms are not exclusive to motion sickness and have a notably different time course than traditional GI disturbance symptoms (Lawson and Mead 1998), often starting prior to nausea and extending past when nausea subsides. Ocular symptoms include the presence of headaches, eyestrain, and difficulty focusing. It is expected that these symptoms are impacted the most by the presence of the VR headset, hence requiring both experimental groups to wear it and keeping the headset brightness constant.

To track subjects' physical wellbeing during centrifugation, they were asked to rate their 'general discomfort' and 'nausea' on a scale of 'none', 'slight', 'moderate', and 'severe' every five minutes. During wave-like motion, these questions were asked every minute. A stopping criterion was established to prevent emesis during wave-like motion: if subjects rated moderate nausea for two consecutive check-ins (i.e., separated by 1 min), the wave-like motion stopped early.

In addition to tracking motion sickness, we collected state anxiety scores at the same intervals as the full MSQ. Previous studies have found correlations between the development of state anxiety and motion sickness (Stelling et al. 2021), suggesting it would be a useful metric. This connection between anxiety and motion sickness may be related to a potential link between the emotional and vestibular neural networks wherein mental and physical mobilization for action occur along the same mental pathways (Clément et al. 2020). Anxiety was scored using a six-question modified State Trait Anxiety Inventory (STAI) (Marteau and Bekker 1992) which asks subjects to rate declarative statements

about their mental wellbeing on a scale of 'not at all', 'somewhat', 'moderately so', and 'very much so.' This modified STAI focused on state anxiety which refers to feelings in the moment, rather than general anxiety. As is typical, statements were rated on a scale of 1–4 with the highest number being associated with the worst feeling. Similarly, these numbers are summated for all statements at each time point resulting in a minimum STAI of 6 and a maximum of 24. Every five minutes, the subjects scored the full MSQ and the STAI verbally. This continued at the same frequencies throughout the recovery period as well.

Objective data regarding subject sensorimotor impairment was collected as a secondary metric using the Modified Romberg balance test (Agrawal et al. 2011; Bermúdez Rey et al. 2017), specifically 'condition 4' focused on isolating vestibular-mediated contributions. For this, subjects were tasked with balancing on a foam mat with their arms crossed, feet together, and eyes closed for 30 s. Failure criteria included uncrossing arms, separating feet, opening eyes, or otherwise losing balance and requiring stabilizing support from test conductors. These trials were performed eight times each at three different points throughout the experiment. A baseline was taken prior to centrifugation, another set was performed after wave-like motion, and a final set after the hour of recovery following wave-like motion. Pass/fail metrics were collected as well as acceleration and gyroscope sway data sampled at 25 Hz from an inertial measurement unit (IMU) positioned on the subject's central lower back. Sway was characterized as the inertial XY-plane (perpendicular to gravity) RMS of linear acceleration during modified Romberg trial prior to completion or failure.. Prior to the first set of trials, subjects were incremented through a series of easier tasks where they were instructed to balance on solid ground and/or with their eyes open for 30 s. Subjects only performed these tasks once, resulting in three practice tasks before the first set of eight full balance trials.

Experimental design

This study used a between-subject design where experimental groups were balanced by sex and motion sickness susceptibility such that the mean and standard deviation of the Short-Form Motion Sickness Susceptibility Questionnaire (MSSQ) percentile scores were statistically equivalent while maintaining a similar number of female subjects. The MSSQ (Golding 1998, 2006) is a commonly used (Bretl et al. 2019; Bretl and Clark 2020; Irmak et al. 2021) questionnaire that rates subject susceptibility to terrestrial motion sickness as a population percentile based on their history with terrestrial motion sickness. Potential subjects with MSSQ scores in the outer 5th percentiles were excluded from the study to pre-emptively remove outliers. While the MSSQ was not designed to capture susceptibility to non-terrestrial forms of motion sickness, it has been shown to effectively predict sickness scoring during parabolic flights (Golding et al. 2017) and therefore may be extendable to SMS and EMS.

Subject recruitment was primarily done via flyers posted in the laboratory building, yielding a cohort of mostly college-aged engineering students.

Participants

There were 30 total participants across the two experimental groups (age = 23.4 ± 3.5 years, female = 11, MSSQ = 38.4 ± 21.1%) with 15 subjects in each. The control group (female = 5, age = 23.2 ± 3.6 years, MSSQ = 38.3 ± 19.5%) was provided the fixation point while the visual countermeasure group (female = 6, age = 23.5 ± 3.5 years, MSSQ = 40.6 ± 24.0%) was provided accurate visual cues. A graphical representation of the spread of MSSQ scores is available in Fig. 3. Wilcoxon Rank Sum tests for independent samples confirmed that the two groups were not from significantly different populations in terms of their past susceptibility to motion sickness (W = 104, p = 0.74), their sickness score prior to wave-like motion (W = 98.5, p = 0.57), nor their state anxiety prior to wave-like motion (W = 119.5, p = 0.78). All participants signed a written informed consent prior to participating in the study. The study was approved by the Institutional Review Board of the University of Colorado, Boulder.

Data analysis

Data visualization was performed in MATLAB R2021b (The Mathworks, Inc). Multiple subjects did not complete

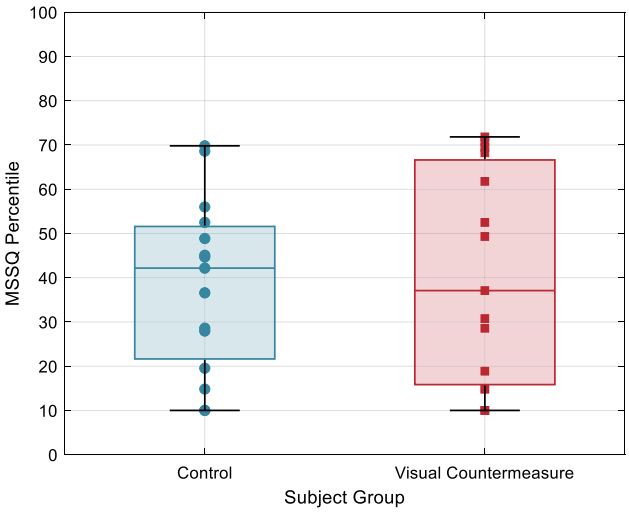

Fig. 3 MSSQ spread between experimental groups. Individuals within the control group (blue) are denoted by circles, and individuals with the visual countermeasure group (red) are denoted by squares

the hour of wave-like motion due to reaching the stopping criteria of two minutes of moderate nausea. This yields a potentially biased sample among the surviving subjects in metrics such as MSQ and STAI. As a rudimentary adjustment for this, when a subject reached the stopping criteria, based upon their available data during wave-like motion we linearly extrapolated their responses (MSQ score, STAI score) for the later time points they did not complete. If a subject only had one data point during wave-like motion, the first recovery data point was used with the amount of time the subject experienced wave-like motion for the linear extrapolation (this only occurred for one of our 30 subjects). In these cases, extrapolated data points are specifically denoted (open shapes and dotted lines). To maintain robustness for this rough approximation, median values of MSQ and STAI were used for graphical visualization and non-parametric statistics were similarly employed. Statistical analyses were performed in both MATLAB and R 4.3.0 (RStudio 2023.03.0 + 386).

To investigate factors that may impact the MSQ subcategory scores, we created a series of cumulative link regression models that were fit with the ordinal scores at the wave + 55 time point. This point was selected because it is the last time point that contains extrapolated data for subjects that dropped out of the study and conservatively estimates the MSQ at the end of wave-like motion. The model parameters include MSSQ scores and experimental group. This allows for testing the effect of the countermeasure (relative to the control), while isolating inter-individual variability that could be explained by each individual's MSSQ score.

Two more cumulative link models were developed to determine if there is a relationship between full MSQ scores and experimental group, MSSQ and STAI scores independently at two relevant time points. Based upon SpaceX's Dragon landings to date, nominal capsule recovery is expected to take place approximately 30 min following splashdown with the final crewman removed from the capsule at 55 min following splashdown (Dervay 2023). Therefore, MSQ scores were fit with the model at both wave + 30 and wave + 55.

Results

For all 30 subjects, individual sickness and anxiety progressions during the wave-like motion were plotted with linear extrapolations for subjects that did not complete the full hour. The final full MSQ and STAI taken during wave-like motion were performed at time wave + 60 as the profile comes to a stop and the recovery period begins, labeled as recov + 0. For subjects with extrapolated data, the final full MSQ and STAI scores available were set as the recov + 0 data points.

MSQ scores

Full MSQ scores over time are shown in Fig. 4 (Fig. 4a depicts the time history of each subject in the control group, and Fig. 4b contains the visual countermeasure group). The median scores for both experimental groups along with the 25th and 75th percentiles are shown in Fig. 4c. Neither the median values nor the quartile bounds differ between the two experimental groups.

For the GI disturbance MSQ subcategory, there was a slight difference between the two experimental groups, as evidenced by Fig. 5a. While the quartile ranges overlapped the entire duration of the experiment, the median of the control group diverted from the visual countermeasure group at around wave + 30 resulting in slightly higher GI disturbance. This difference quickly disappeared during recovery as the scores converge.

The time course of MSQ sopite symptoms during wave-like motion and recovery are displayed in Fig. 5b. The scores did not vary between the experimental groups, but the development of sopite symptoms was different than the progression of MSQ GI symptoms. Unlike the divergence between experimental groups and the increase in the GI disturbance score at wave + 30, the sopite scores of both groups increased steadily from the beginning of wave-like motion.

Finally, the time course of MSQ ocular symptoms is shown in Fig. 5c. The values between the experimental groups were slightly different with the control group median being offset from the countermeasure group, but this difference was well within the 25–75 percentile bounds of each group.

For all three of the subcategories, neither the MSSQ percentile, nor the experimental group variable reached significance, but the closest was the effect of experimental group on the GI score ($\Delta\ GI_{55} = 2.17$, $\beta = -1.204$, $p = 0.073$).

STAI

STAI scores are plotted similarly to the MSQ scores, with individual scores for each experimental group shown in Fig. 6a and Fig. 6b and median scores in Fig. 6c with the quartile ranges shown. Subjects in the control group have higher median STAI scores throughout the wave-like motion and have a larger spread of anxiety throughout recovery when compared to visual countermeasure group.

The cumulative link models found that the only significant factor in predicting MSQ scores is the STAI score at the same time point (wave + 30: $z = 3.58$, $p = 0.00034$; wave + 55: $z = 3.65$, $p = 0.00026$). Combining both time points, a Spearman Rank correlation test was run and found that there was a moderately high correlation between MSQ score and STAI score ($\rho = 0.65$, $p < 0.0001$), suggesting that

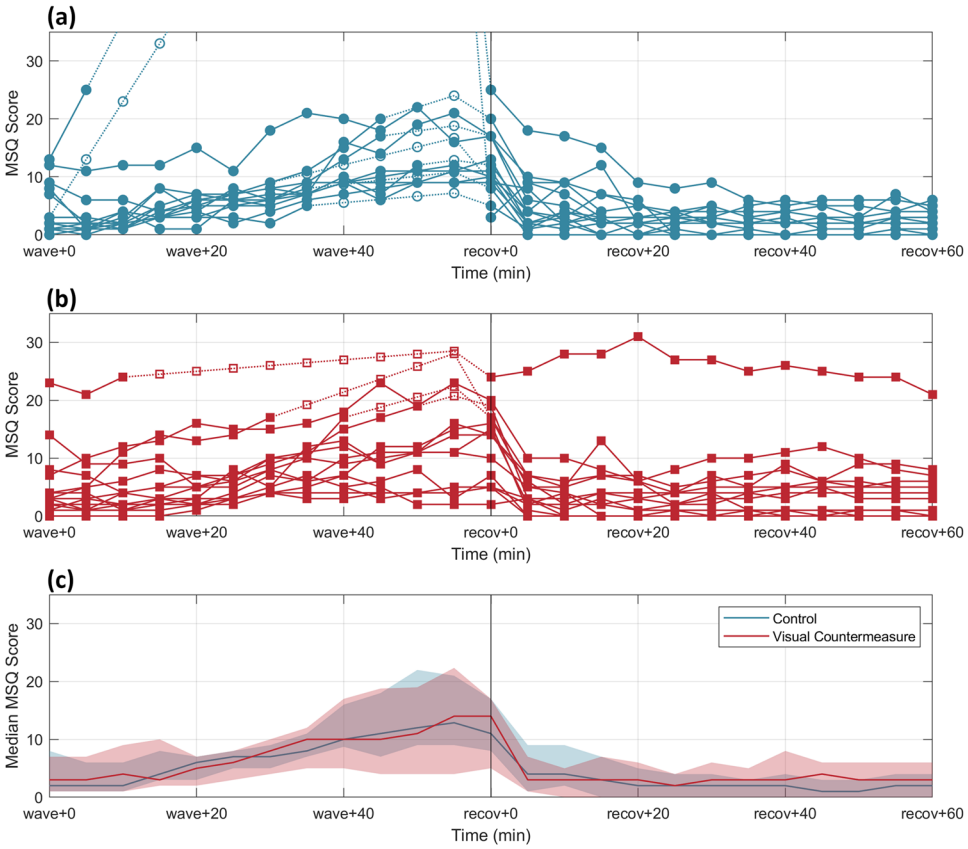

Fig. 4 **a** Time course of MSQ score for the control group. **b** Time course of MSQ scores of the visual countermeasure group. **c** Time course of median for both experimental groups with 25th and 75th percentiles shown. Across subplots here and throughoutt this work, the control group is depicted with blue coloring (with individual reports denoted with circles) and the visual counteremeasure group is depicted with red (with individual reports denoted with squares). Extrapolated data is noted with empty markers and dotted lines

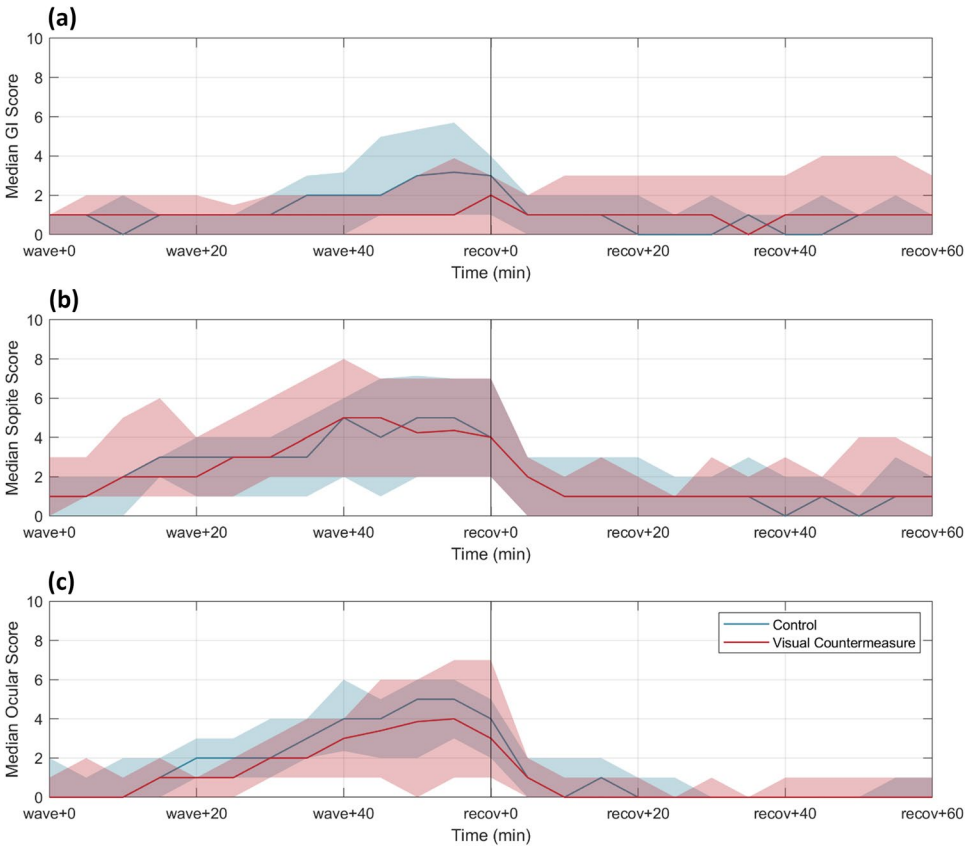

Fig. 5 Time course of median scores for **a** GI disturbance, **b** sopite syndrome, and **c** ocular symptoms along with quartile ranges

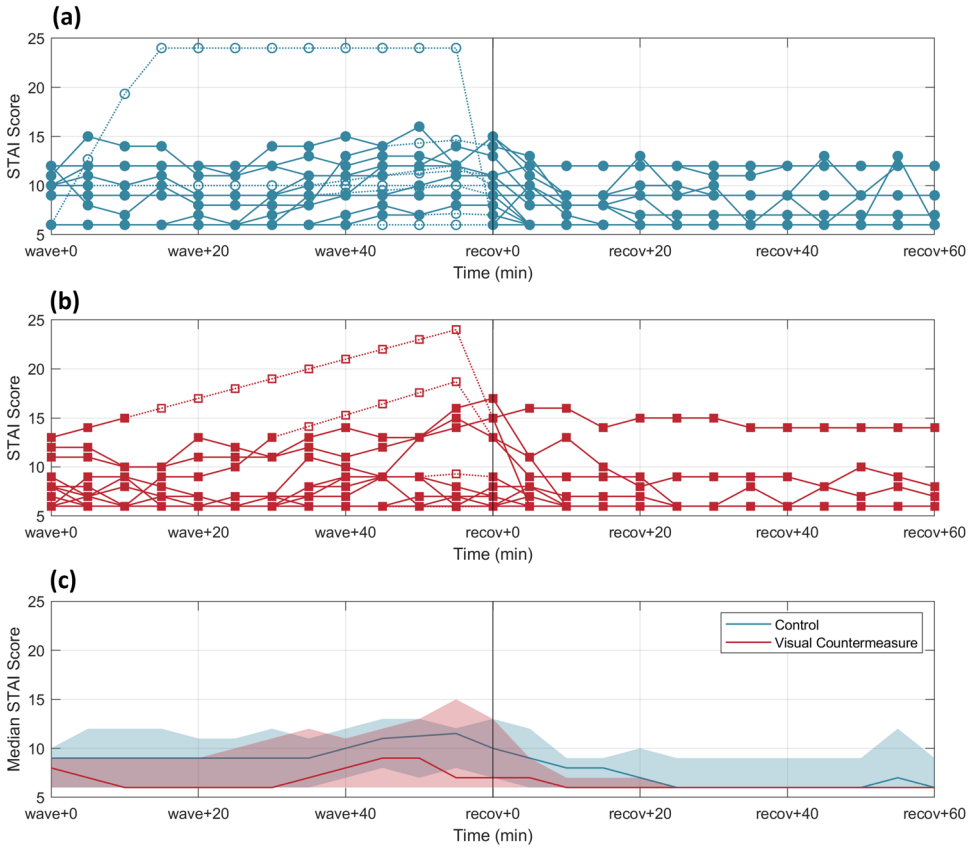

Fig. 6 **a** Time course of STAI score for the control group. **b** Time course of STAI scores of the visual countermeasure group. **c** Time course of median for both experimental groups with 25th and 75th percentiles shown

physically unwell subjects also demonstrate higher amounts of state anxiety.

Nausea

During wave-like motion and recovery, subjects rated their general discomfort and nausea every minute. The high-resolution time course of these nausea ratings during the wave-like motion are shown in Fig. 7.

Subjects in the control group (Fig. 7a) tend to have a higher incidence of moderate motion sickness, as well as quicker development. Like the divergence shown in Fig. 5a at wave + 30, at the halfway point of wave-like motion, the rate of nausea development accelerates in control subjects while it otherwise remains fairly constant in the countermeasure group.

Survival

Subjects who expressed two consecutive reports of moderate nausea (i.e., separated by one minute) during wave-like motion were stopped early to prevent emesis during the experiment. Figure 8 shows the time course of percentage of subject survival between the two experimental groups. Only 33% (SE: ± 8.78%) of the control group (n = 5/15) was able to survive the full hour of wave-like motion. In contrast, 79%

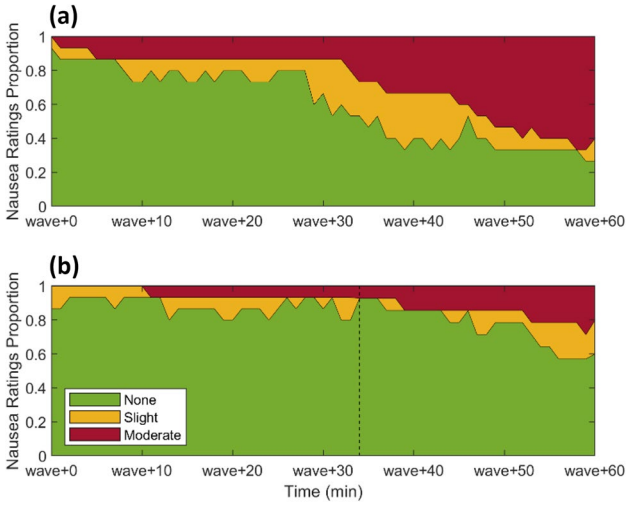

Fig. 7 Nausea ratings during wave-like motion for **a** the control group and **b** the visual countermeasure group. The dashed black vertical line denotes a subject dropout due to technical issues, thereby shrinking the subject pool by one. From top to bottom, moderate (red), slight (yellow), and none (green) nausea ratings are described as a percent of total reports. The ratings of subjects that dropped out were frozen for the remainder of the hour

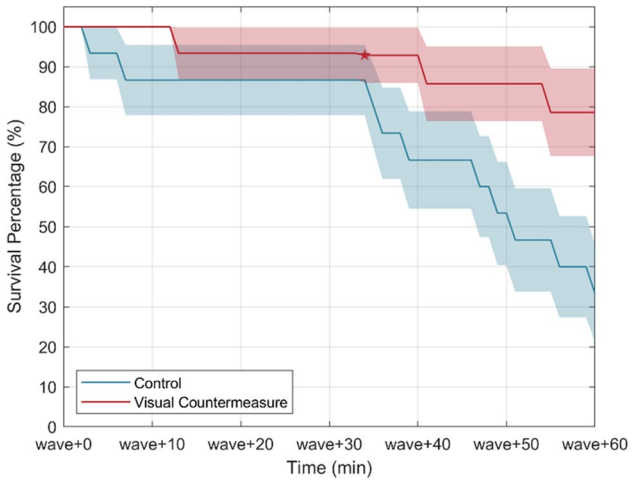

Fig. 8 Time course of survival between experimental groups during wave-like motion. The shaded regions are the standard error of the proportions. The red star denotes a subject dropout due to technical issues, treated as no dropout

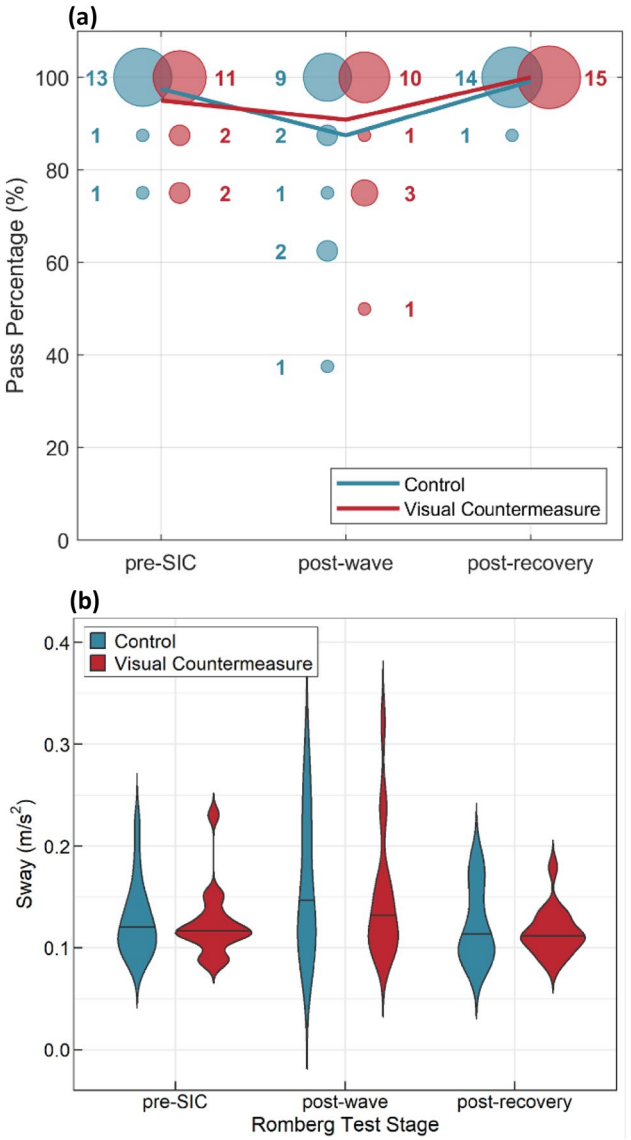

Fig. 9 **a** Average and lumped pass percentages where the bubble size indicates the number of subjects with that score and **b** Inertial XY-plane RMS of acceleration sway during the modified Romberg balances tests

(SE: ± 6.44%) of the countermeasure group (n = 11/14) was able to complete the wave-like motion.

As expected, since this metric is directly related to nausea, we see the same divergence at wave + 30 where control group subjects demonstrate accelerated drop-out due to a faster onset of moderate nausea.

A logistic regression model was developed to determine the impact of experimental group and individual MSSQ on whether a subject would survive the full hour of wave-like motion. The model found that MSSQ did not have a significant effect on predicting subject survival ($z = -0.295$, $p = 0.768$) while the experimental group did ($z = 2.138$, $p = 0.0325$). As any effect of the countermeasure could have confounded a relationship, we repeated this analysis within just the control group, but again found no association between MSSQ and surviving the wave-like motion ($z(14) = -0.731$, $p = 0.465$). To follow up, a two-tailed t-test for proportions was used to directly compare the survival proportions between the two groups at wave + 60 and found a significantly higher survival rate in the visual countermeasure group than the control group ($t(14) = 2.50$, $p = 0.027$).

Balance

Two objective measurements were performed to assess balance throughout the experiment. The percentage of modified Romberg balance trials successfully completed at each stage of the experiment is shown in Fig. 9a, while the median off-axis sway is shown in Fig. 9b. For both metrics, it is important to note that subjects that reached the stopping criteria did not undergo a full hour of wave-like motion, and as a result, may not have experienced the same amount of imbalance as those that did. Since more control subjects dropped out than countermeasure subjects, this may introduce a bias in balance outcomes between the experimental groups.

Figure 9a shows that some subjects experienced balance decrements (i.e., lower pass percentage) after the wave-like motion relative to before the SIC protocol; however, the presence of a visual countermeasure does not seem to impact the number of successfully completed balance tasks. Additionally, regardless of experimental group, subjects were able to reach or improve their baseline performance by the end of an hour of recovery.

Figure 9b shows a similar trend to Fig. 9a in relation to the impact of SIC and wave-like motion on balance. Just as suggested by the pass percentages, which are imprecise measurements of balance, sway increases as a result of SIC and wave-like motion and improves upon or returns to baseline after an hour of recovery.

Wilcoxon Rank Sum tests of independent samples performed at each test stage found no significant differences between experimental groups ($p > 0.05$). Therefore, we combined the two experimental groups at each time point and ran a Friedman test for sway across test stages. Here we found that there was a significant relationship between sway and test stage ($\chi^2(2)=18.2$, $p=0.0001$). Post-hoc Wilcoxon Rank Sum tests with a Bonferroni correction concluded that only the difference between post-wave and post-recovery sway was significant ($p=0.0004$), and the difference between pre-SIC and post-wave sway was marginally significant ($p=0.056$).

Discussion

The purpose of this study was to determine if providing motion-congruent visual information via VR is an effective avenue for improving motion tolerability and reducing the incidence of motion sickness in astronauts during post-flight water landings. We used a ground-based reentry analog to mimic the subsequent effects of transitioning from microgravity to Earth gravity followed by wave-like motion. Half of our subjects were provided with visual cues of self-motion while the other half were provided with a head-fixed fixation point, both in a VR headset. Supporting our primary hypothesis, the countermeasure group had a significantly better survival rate after an hour of wave-like motion. Specifically, with the pre-defined stopping criteria of two consecutive reports of 'moderate' nausea (separated by one minute), more than twice as many subjects with the countermeasure completed the one hour of wave-like motion than the control group. Additionally, while we did not see any significant differences in multisymptomatic motion sickness (MSQ) scores between the visual and control groups, we did find significant evidence correlating MSQ and STAI scores as previously suggested in the literature (Lawson 2014a, b; Stelling et al. 2021). In investigating our secondary hypothesis, we detected no differences in sensorimotor performance between the countermeasure and control groups in terms of balance outcomes. However, both experimental groups saw significantly reduced balance performance following the centrifugation and wave-like motion, with inertial XY-plane RMS of linear acceleration (a proxy for sway) significantly higher during the post-wave stage than the post-recovery stage.

This experiment represents the first demonstration that reliable, motion-congruent visual cues of self-motion significantly reduce peak motion sickness symptom severity following an hour of wave-like motion preceded by a ground-based gravity transition analog. In contrast to previous studies that have investigated the efficacy of an artificial horizon (Krueger 2011), this is the first instance in which a visually rich scene providing cues of both tilt and translation has been used. The evidence found—that this visual countermeasure can more effectively bound motion sickness symptoms at and beneath moderate nausea (i.e., increase survivability) than the control—suggests that providing crewmembers similar, motion-congruent visual cues may be an effective avenue of curbing the onset of more severe motion sickness symptoms. Thus, providing either natural or synthetic Earth-veridical visual information may both reduce operational risks (such as vehicle egress) and discomfort following landing, providing crewmembers and commercial space travelers more tolerable experiences. Additionally, this visual countermeasure may be beneficial during future exploration class missions (e.g., landing on the moon or Mars), where crewmembers will not have access to astronaut rehabilitation specialists for support post-landing (S. J. Wood et al. 2011).

While sensory conflict theory provides insight into reducing motion sickness using congruent visual scenes, the conflict would not necessarily be fully eliminated with this methodology. Future computational models of motion sickness, with the capability of modeling motion sickness in the presence of arbitrary motions and arbitrary visual scenes, may enable the construction of visual scenes that result in additional attenuation of motion sickness symptoms. To this end, we anticipate that the individual subject responses provided in this effort may be utilized to inform future computational modeling efforts, provided that neurovestibular changes during the ~ 1 h of SIC, passive motions during the wave-like motion, and visual channels during wave-like motion are all sufficiently modeled.

Additionally, we provide a quantification of sensorimotor impairment and the resultant time course of adaptation (sway, captured during a vestibular-mediated modified Romberg test) following our SIC protocol. While we did not see a difference in sway between experimental groups, the finding that sway is significantly higher following wave-like motion (preceded by SIC) than after recovery provides some time course for the effectiveness of this analog at inducing sensorimotor impairment for use in future studies (i.e., for future use as an impairment paradigm). Furthermore, we suspect that our marginally significant finding between the pre-SIC and post-Wave stages may be confounded with an ordering effect since the pre-SIC balance tests served as practice before the post-wave tests. We likely would have found a significant difference between these two stages if

subjects were given practice trials prior to data collection. It is important to note that these results are impacted by the presence of wave-like motion, which may have induced some level of postural instability or recovery.

Limitations

This study is limited by the paradigms leveraged in this study. We have leveraged the SIC paradigm as an analog to gravity transitions, but actual sensory reinterpretation of Earth gravity cues following a prolonged stint in microgravity will likely result in different time courses of both readaptation and motion sickness symptoms. Additionally, there is high inter-subject variability in susceptibility to the SIC paradigm that cannot be captured by the MSSQ or any other metric presently. This may have resulted in an unaccounted group difference, though MSQ scores prior to wave-like motion did not differ significantly between groups. Moreover, our TTS device was not capable of providing representative Earth-vertical motions experienced by a capsule following splashdown (referred to as heave), which have been found to induce motion sickness for certain frequencies of motion in a cabin environment (O'Hanlon & McCauley 1973). To help address the impact of these analog paradigms, a manuscript on a companion study using alternative gravity transition and sea state exposure with the same countermeasure approach is forthcoming.

Additionally, astronauts returning to Earth after prolonged stays in microgravity are thought to undergo a level of sensory reweighting (Fetsch et al. 2009; Hupfeld et al. 2022) unlikely replicated by our relatively short-duration analog. This reweighting results in an increased reliance on visual information and a decreased reliance on vestibular information, as well as an increased reliance in somatosensory cues. For this reason, we postulate that an operational implementation of our visual countermeasure may result in more efficacy, due to the increased reliance on visual information following splashdown.

Finally, this study is limited by the conveniences afforded by the laboratory setting. We were able to provide motion-congruent visual sensory information to subjects because we knew the wave motion profile ex-ante. In practice, supplying subjects with a visual scene will likely only be possible with some time-lag following actual motion, and such a lag was not present during our experiment. If future implementations of the visual countermeasure are found to have a significant time-lag, it will likely be worth reexamining the efficacy of this visual countermeasure with a lag or considering different methods of implementation. Hock et al. 2017 created an IMU-driven VR environment that enabled car passengers to play a VR game with less motion sickness while driving than when stationary. They used a linear interpolation of speed and rotation to remove lag suggesting that a similar implementation of our visual scene may be able to use the same process (Hock et al. 2017).

Future work

The current study investigated the efficacy of providing a rich visual scene with motion-congruent cues in VR, as compared to only showing a fixation point in VR. Future work should elucidate the role of (1) the visual modality (e.g., VR, external display, natural vision), (2) the rich visual scene vs. simple cues of self-motion (e.g., an artificial horizon line), and (3) the fixation point control condition (which likely suppresses the vestibulo-ocular reflex) vs. a completely dark scene or with eyes closed.

Additional avenues of alleviating symptom severity through non-pharmaceutical means should be explored. Previously in the literature, while examining the development of motion sickness due to horizontal oscillations, symptoms have been found to be affected by the level of back support provided to subjects, while in an upright seating configuration (Mills and Griffin 2000). Future experiments should additionally explore how active postural control influences the development of symptoms and if active postural control can be strategically implemented to reduce symptom severity, using a combination of the entry motion sickness paradigm and visual countermeasure presented in this effort.

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Data availability Additional datasets generated during and/or analyzed during the current study are available on Open Science Framework (OSF) at the following link: https://osf.io/cb4fk/?view_only=c8177c3d215c470c86efe2b5c9e39cc3.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval The studies involving human participants were reviewed and approved by The Institutional Review Board at the University of Colorado Boulder. The subjects/participants provided their written informed consent to participate in this study.

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