Postural Instability and Seasickness in a Motion-Based Shooting Simulation

Kyle A. Pettijohn; Dominick V. Pistone; Andrew L. Warner; Grant J. Roush; Adam T. Biggs

BACKGROUND: Motion sickness is a problem for many; however, it is especially pressing for military personnel who need to operate in life and death environments. The current study investigated the underlying cause of motion sickness by testing postural instability theory.

METHODS: Subjects experienced realistic motion profiles while performing a virtual reality shooting task and reporting any motion sickness symptoms. Postural instability was manipulated within 20 subjects across 2 conditions. In one condition, subjects could readily adapt their posture to the motion profile by adjusting their feet on the platform (Free), and in the other condition, their feet were fixed in place on the moving platform (Fixed). This Free condition decreased postural instability by allowing adjustment, while the Fixed condition increased postural instability by restricting adjustment. The same subjects completed both conditions to control for individual differences in motion sickness susceptibility.

RESULTS: Overall, motion sickness was mild as measured by SSQ ($M = 14.41$, Free; $M = 18.89$, Fixed), and no statistically significant differences were observed between the conditions. Performance on the shooting task was reduced in accuracy by approximately 40%, although this result did not differ between conditions.

DISCUSSION: The results do not support postural instability as a contributing factor in motion sickness symptomology. They also demonstrate the importance of accounting for motion when conducting training.

KEYWORDS: simulator sickness, motion sickness, sensory conflict, postural instability, virtual reality.

Pettijohn KA, Pistone DV, Warner AL, Roush GJ, Biggs AT. *Postural instability and seasickness in a motion-based shooting simulation*. Aerosp Med Hum Perform. 2020; 91(9):703–709.

Motion sickness (MS) poses a particular difficulty for the armed forces where performance will suffer due to its effects, often with severe consequences. For example, Naval gunners operating on small boats in choppy waters will not be able to successfully target the enemy if they are suffering severe nausea. Because the etiology of MS is not known and susceptibility differs across individuals, most efforts have been aimed at mitigating symptoms rather than preventing the circumstances that cause motion sickness. Many treatments for relieving MS symptoms are pharmacological, and although the treatments can be effective, they often introduce the risk of adverse side effects such as drowsiness.[19] These side effects preclude the use of pharmacological interventions in many operational environments. Motion sickness may also occur when using virtual reality (VR), augmented reality (AR), or any sort of mixed reality devices, although the symptoms are sometimes referred to as simulator sickness rather than motion sickness when using a simulator despite the similarity between the actual symptoms (e.g., Geyer and Biggs[5]). Interest has come from the gaming industry, engineering companies, healthcare providers, and various companies looking for unique ways to market their products are adopting VR technology.[10]

VR likewise offers great opportunities for the military to enhance both operations and training. For example, VR devices may be used to simulate shipboard tasks or aerial maneuvers without the cost or danger of performing these tasks in the operational environment. Although VR has great potential as a cost-effective training platform, this potential may be limited by issues involving MS. It is already known that VR alone may cause people to feel nauseous, eyestrain, and develop

From the Naval Medical Research Unit Dayton, Wright-Patterson AFB, OH; The Henry M. Jackson Foundation for the Advancement of Military Medicine, Bethesda, MD; and the Oak Ridge Institute for Science and Education, Oak Ridge, TN.

This manuscript was received for review in October 2019. It was accepted for publication in June 2020.

Address correspondence to: Kyle Pettijohn, Ph.D., 2624 Q St. Building 851, Area B, Wright-Patterson AFB, OH 45433; kyle.pettijohn.ctr@us.af.mil.

DOI: https://doi.org/10.3357/AMHP.5539.2020

headaches[4,13]—symptoms which would likely only be exacerbated by motion. Again, being able to pinpoint the cause of MS and prevent it will help ensure that VR is used effectively while avoiding operational impairments due to motion sickness.

Several theories have been put forth to explain the cause of MS, but the most commonly accepted theory is sensory conflict theory (SCT). SCT proposes that differences in sensory input generated as a result of unusual or provocative motion leads to MS symptoms.[15,16] For example, a passenger sitting in the backseat of a car may feel the car accelerate and turn but not see a corresponding change in visual flow. Thus, there may be a mismatch between vestibular and visual motion. These conflicting signals are sent to a theoretical "comparator" which compares the incoming information to the "neural store." The neural store contains information regarding the motion the passenger has experienced in the past. If the conflict between the current and past information is too large, a mismatch signal is generated which, in turn, begins the autonomic response of MS.[15,16,22] According to SCT, it is possible for people to adapt to unusual motion by updating the neural store, thus reducing the strength of the mismatch signal. This updating can be seen when aviators experience motion sickness when first operating flight simulators, but most become accustomed to the sensations caused by the simulator over time, given proper spacing of flights.[8,15,16]

Several hypotheses related to SCT also attempt to describe the etiology of MS. For example, one explanation is that MS is caused by changes in one's subjective vertical orientation.[1] According to this hypothesis, people compare their expected state as sensed by the visual, vestibular, and proprioceptive systems to the body's actual state. When the mismatch between these two outcomes is detected, MS ensues. The ability to minimize this mismatch explains why drivers, who can better adjust their posture in anticipation of changes in acceleration or tilt, tend to experience less motion sickness than passengers.[3] Support for this idea comes from a series of experiments in which subjects saw a rotating visual field. When earth-vertical cues were removed (thus decreasing subjects' ability to maintain an accurate representation of verticality), their stability was reduced as measured by center of pressure on a force plate. These subjects also reported higher subjective ratings on a misery scale.[11] This explanation suggests a somewhat different type of conflict (i.e., what is expected vs. experienced with respect to gravity) is responsible for producing MS.

Other theories attempt to explain why certain motions give rise to MS. For example, the poison hypothesis suggests that motion sickness—particularly emesis—is an evolutionary adaptation to ingesting toxins. The side effects of ingesting poisons include dizziness, nausea, and sweating, and the body's response is to rid itself of the offending substance as quickly as possible. According to this view, the same response is elicited when exposed to provocative motion as an accidental byproduct.[23] Another view is that MS may result from evolutionary advantages to help humans avoid ingesting poison, where disruption in the vestibular-visual system could provide an ideal early detection methods for toxins.[12,24] A related notion is that nausea elicited by motion sickness provides negative reinforcement akin to pain, so the person is less likely to engage in the behavior that elicited MS in the first place.[12]

Among the alternate theories of MS, one of the most studied and published about theories is Postural Instability Theory (PIT), which is rooted in ecological perception theory. Riccio and Stoffregen[17] defined postural stability as "the state in which uncontrolled movements of the perception action systems are minimized" (p. 202). PIT's authors noted that an individual's sensory information was incongruent even in normal, everyday tasks, and therefore SCT was unable to explain why some individuals are susceptible to MS and others are not.[17,18,20] According to PIT, people must change their posture to adapt to different types of motion. If this does not happen, the uncontrolled movements driven by the provocative motion will eventually lead to MS. Thus, changes in posture during exposure to motion should be predictive of MS symptoms. Indeed, a series of studies in which subjects stood while the room around them moved found that postural sway increased before they reported feeling subjective symptoms of MS.[18,21] One of the implications of PIT is that those who can successfully adapt their posture should be able to avoid, or at least experience reduced, MS.

The current study evaluated the impact of postural instability on motion sickness symptoms by directly manipulating postural stability across two conditions that incorporated physical motion. In one condition, subjects could naturally adapt posture and balance during the motion by readily adjusting their feet on the platform (Free condition). In the other condition, subjects could not easily adapt posture and balance to the motion because their feet were affixed to the motion platform (Fixed condition). This paradigm has been shown to effectively and objectively manipulate postural instability.[14] However, subjects in the previous experiment conducted only a passive task that involved occasionally counting backward. This passive environmental observation is not representative of a more operational task, which could affect symptomology in different ways. For example, the passive engagement could have exacerbated symptoms in both conditions by not providing a meaningful visual stimulus upon which subjects could focus.[2] This difference could potentially mask any effect of postural instability by provoking symptoms in both conditions, or postural instability could manifest differences in more objective and operationally meaningful ways by having an impact on performance in an operational task with active engagement. To test these possibilities, the current experiment included a more engaging task with a virtual reality naval simulation that required engaging hostile craft while operating a 0.50 caliber machine gun.

There were two aims to the current experiment. The first aim was to examine any differences in adaptive behavior and MS symptoms. Postural control should be different in the Free versus Fixed stance conditions,[14] and according to PIT, this difference in postural instability should exacerbate motion sickness symptoms in the condition with greater postural instability. However, we hypothesize that despite the increased instability due to motion, there will be no differences in symptomology. This finding would confirm that the previous evidence cannot be explained by a task-related difference due to passive engagement versus active engagement. The second aim was to quantify changes in performance brought about by motion and whether postural instability directly impacted performance. We hypothesize that performance on the shooting task will be worse under motion, although it is unclear whether postural instability will directly impact performance.

METHODS

Subjects

An a priori power analysis with medium effect size ($F = 0.3$) found that 14 subjects are required to have an observed power of 0.86 with alpha set at 0.05. The study protocol was approved by the Naval Medical Research Unit – Dayton Independent Review Board. Subjects included 20 people (4 women) recruited from active duty military members and those covered by Department of Defense insurance at Wright-Patterson AFB, OH. They were between the ages of 18 and 34 yr (M = 27.5, SE = 0.9) The preliminary screening asked potential subjects about any conditions, medication, or activities (e.g., blood or plasma donation within the last 30 d, alcohol consumption) that might prevent them from taking part in the study, and the compliance questionnaire ensured that subjects met the eligibility requirements for each session. Subjects were also informed that they must refrain from drinking alcohol for 24 h before an experimental day and avoid taking any medication that could affect balance, inner-ear fluid levels, or cause dizziness or lightheadedness in order to maintain eligibility. Female subjects were administered a pregnancy test to ensure that pregnancy-related nausea would not affect the results. Subjects were blinded as to the purpose of the study and took part in the experiment on two separate days, with a minimum of 2 d between sessions (M = 2.55, SE = 0.30).

Materials and Apparatus

The experiment employed a within-subjects design with each subject participating in both the Free Stance and Fixed Stance conditions. The order of the conditions was counterbalanced to account for any confounding effects of order. For the Fixed Stance condition, subjects' feet were strapped into modified snowboard bindings to reduce their ability to make postural adjustments. The bindings were placed 9 in (22.86 cm) apart from center to center. The modifications consisted of removing the straps, buckles, and hibacks as these could provide additional support. Thus, the modified bindings contained the baseplate, sideplates, and heelcups (**Fig. 1**). This manipulation has successfully reduced postural stability in the Fixed condition in the past as measured by ellipsis area and sample entropy in the lateral axis.[14] Subjects exhibited larger ellipsis areas, $\eta_p^2 = 0.28$, which represents a larger magnitude of postural sway in the Fixed stance condition. Subjects also exhibited higher entropy, $\eta_p^2 = 0.74$, in the Free condition, which indicates that they were able to make larger and more complex adjustments to maintain stability. This evidence indicates that a Free stance versus Fixed stance is an effective means to independently manipulate postural stability between conditions, especially given the relatively large effect sizes for effects comparing postural stability in the Fixed stance versus Free stance conditions. Additional details about quantifiable attributes of postural stability are available in Pettijohn et al.[14]

Procedure

Subjects completed a series of three 10-min simulated sea state profiles in either the Free Stance or Fixed Stance condition. The first profile was a No Motion condition, in which the platform was powered on but did not move. The remaining two profiles consisted of motion created from real-world "sea state data" taken from affixing accelerometers to a small boat as it traveled across a bay. The profiles differed in that the second was created by removing the first minute of collected sea state data and appending it to the end of the profile. The order of the motion profiles was counterbalanced across subjects as well.

During the experimental sessions, subjects completed the Motion Sickness Susceptibility Questionnaire Short-form (MSSQ[16]), the Simulator Sickness Questionnaire (SSQ[8]), a demographics and compliance questionnaire, and a preliminary screening. The MSSQ assesses how susceptible a person is to motion sickness and the kinds of motion that are most likely to cause it. The SSQ measures the severity of motion sickness symptoms a person is currently experiencing. It consists of three subscales: Nausea, Oculomotor Discomfort, and Disorientation. The three subscales can be combined to arrive at a Total SSQ score. Only the SSQ was administered during the study (between profiles and after the final profile).

Motion was conveyed through a 6 degree of freedom Stewart platform that moves in the x, y, z, yaw, pitch, and roll axes; however, only the pitch and roll axes were used for this experiment. Thus, the motion of the platform mainly consisted of roll and pitch perturbations, with occasional more pronounced movements caused by encountering a large wave. Median roll frequency was 0.909 Hz and median pitch frequency was 1.001 Hz. The platform was equipped with safety railing on all sides and was covered with a nonslip surface.

Subjects wore an HTC Vive headset that displayed a virtual seascape created in Unity (Version 5.4; Fig. 1). The resolution of the headset is 1080 × 1200 per eye, subtends approximately 110° of field of vision, and refreshes at 90 Hz. The task during all three profiles was to destroy hostile ships by aiming a mock M2 Browning 0.50 caliber machine gun and pressing a controller button to fire. The mock machine gun was mounted to the front of the platform, with a controller affixed where the trigger would be. Subjects moved the weapon in real space to aim. The task is based on a Navy research project, GunnAR, which is a VR/AR Navy technology prototype developed to provide visual instructions from a gunnery liaison officer on a heads up display to a sailor operating a machine gun. When the ship appeared, subjects saw a "Destructive Free Fire" instruction in all capital red letters at the top of the display. They were told to fire at the ship until 10 rounds hit the "critical region" of the ship (approximately the front third of the ship). If 10 rounds hit the critical

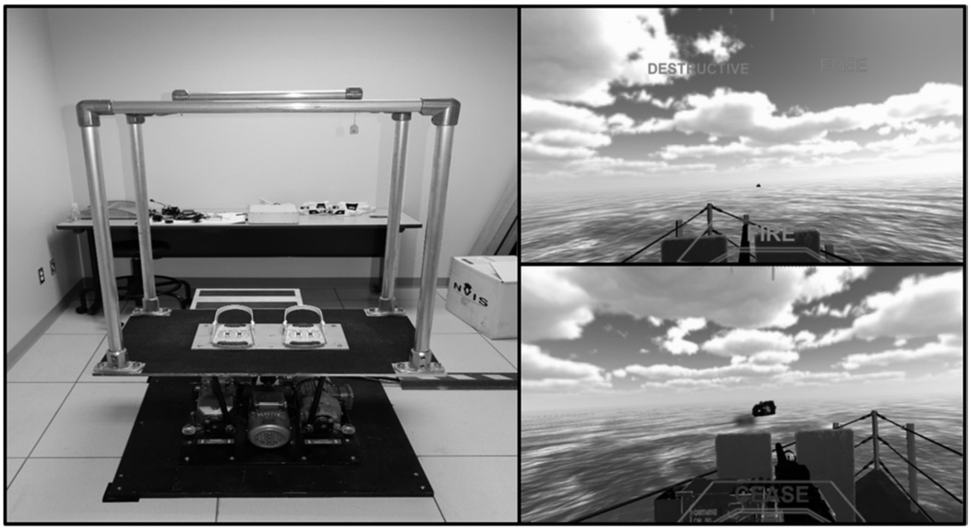

Fig. 1. Image of the motion platform (left) with bindings for the Fixed condition. The Free condition used the same setup with the bindings removed. The right images show the environment for the shooting task with a fire instruction (top) and cease fire instruction (bottom). (Source: NAMRU-Dayton.)

region, the ship would billow black smoke, and an explosion would be heard through external speakers. In addition, a "Cease" command would appear in all capital blue letters at the bottom of the headset. If they did not strike the critical region with 10 rounds, the "Cease Fire" command would appear when the hostile ship was approximately parallel to the subjects's ship. There were 10 ships presented in each profile, at a rate of approximately one per minute. Ships randomly approached on both the starboard and port sides and could take one of two straight paths that passed nearer or further from the subject's ship. Each enemy ship subtended approximately 1.3° x 0.9° of visual angle when it appeared and increased to approximately 6.3° x 3.6° (near) or 4.6° x 2.3° (far) if it was not destroyed in time. Note that these values are approximate, and the visual angle when the subject disengaged could vary based on subject comfort. Time between profiles was long enough to verbally administer the SSQ (approximately 1 min).

RESULTS

A one-way ANOVA was conducted on the two motion profiles to determine if one was more likely to cause motion sickness than the other. There was no significant difference between SSQ scores on the two profiles, $t < 1$; thus, profile was not considered in further analyses. Additionally, SSQ scores were compared between sessions to ensure that no increase/decrease in sensitivity to motion had occurred. There was not a significant difference, $t < 1$. Instead, the time of exposure (Baseline, No Motion, Scenario 1, Scenario 2) was included as a factor. Results for SSQ data are presented in **Fig. 2** and **Table I**. To determine the effect of stance on sickness, Total SSQ scores were submitted to a 2 (Stance) × 4 (Time) repeated-measures ANOVA. There was no main effect of Stance [$F(1,19) = 1.45$, $P = 0.243$, $\eta_p^2 = 0.07$], but a main effect of Time [$F(3,57) = 17.50$, $P <$ 0.001, $\eta_p^2 = 0.48$]. Additionally, the interaction was not significant [$F(3,57) = 1.04$, $P = 0.383$, $\eta_p^2 = 0.05$]. The main effect of time demonstrates that the effects of motion sickness accumulate, thus symptoms become more severe. This finding is important for the methodology as it confirms that this motion profile is indeed capable of inducing motion sickness symptoms.

MSSQ scores were also examined to determine how preexisting susceptibility may have impacted the results. The mean Total MSSQ score for the sample was 11.56 (SE = 2.71), which is slightly higher than the 50th percentile score reported by Golding (2006, in Lamb and Kwok[10]) of 11.3, and somewhat lower than the 50th percentile reported by Lamb and Kwok[9] of 15.8. Thus, it does not appear that the results were skewed by an increased/decreased propensity for motion sickness. An ANCOVA using MSSQ score as the covariate showed the same pattern of results: no effect of Stance, a main effect of Time, and no interaction. Each subscale of the SSQ was also subjected to a 2 (Stance) × 4 (Time) repeated-measures ANOVA. The Nausea and Oculomotor subscales showed the same pattern of results as before; the Disorientation subscale was somewhat different. There was no main effect of Stance [$F(1,19) = 3.50$, $P = 0.077$, $\eta_p^2 = 0.16$], a main effect of Time [$F(3,57) = 8.64$, $P < 0.001$, $\eta_p^2 = 0.31$], and a significant interaction [$F(3,57) = 2.97$, $P = 0.039$, $\eta_p^2 = 0.14$]. Simple effects tests showed that for the Free stance condition, there was a significant effect of Time [$F(3,57) = 8.24$, $P < 0.001$, $\eta_p^2 = 0.30$]. For the Fixed stance condition, the effect of Time was also significant [$F(3,57) = 5.11$, $P = 0.003$, $\eta_p^2 = 0.21$]. In both cases, symptoms increased over time; however, the increase was more severe in the Free stance condition ($M_{increase} = 20.18$, SE = 6.42) than in the Fixed stance condition ($M_{increase} = 11.83$, SE = 4.87).

Because SSQ scores are often not normally distributed, the data were also analyzed using Wilcoxon signed rank tests. Comparisons of both Stance conditions at each time point showed no significant differences, smallest $P = 0.190$. Each subscale of the SSQ was also compared for both conditions; there were no significant differences, smallest $P = 0.060$.

Additional analyses focused upon the human performance data from the simulated shooting task. The shooting measures collected included the number of shots fired, number of rounds on ship, and time to disable hostile ship. However, because all of these measures were highly related and showed roughly the same pattern of results, we focused on accuracy. Accuracy was defined as the number of shots that hit the target (including both the critical and noncritical regions of the ship) divided by

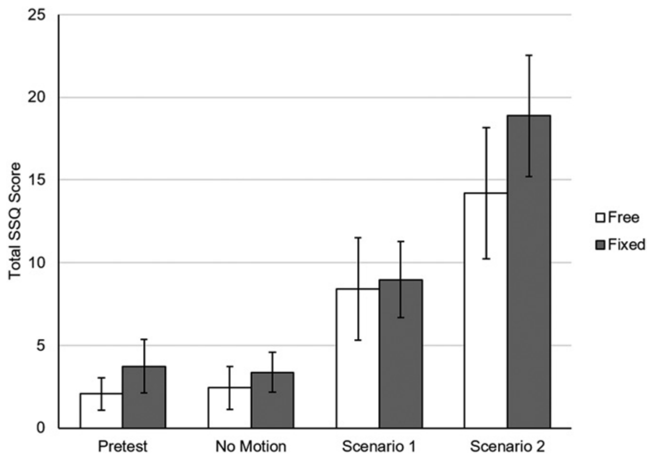

Fig. 2. SSQ scores over time for each condition. Error bars represent the standard error of the mean.

the total number of shots fired. These data were submitted to a 2×3 within-subjects ANOVA with the conditions of Stance (Free or Fixed) and Scenario (No Motion Scenario, First Motion Scenario, Second Motion Scenario). Both motion scenarios simulated the same physical motion, but the two are separated due to the inherent and meaningful time difference in the order of their completion. There was no main effect of Stance, $F < 1$, but there was a main effect of Scenario [$F(2,38) = 130.59$, $P < 0.001$, $\eta_p^2 = 0.87$] (**Fig. 3**). The interaction did not reach significance, $F < 1$. The main effect of Scenario shows that people performed better in the No Motion scenario compared to the two motion-based scenarios (53% compared to 14% and 12%, respectively). Bonferroni corrected pairwise comparisons of the scenarios showed performance was better in No Motion than Scenario 1 [$M_{diff} = 39.3\%$, $P < 0.001$, 95% CI (31.5%, 47.2%)] and better in No Motion than Scenario 2 [$M_{diff} = 41.0\%$, $P < 0.001$, 95% CI (35.1%, 46.9%)]. There was no difference between Scenario 1 and Scenario 2 [$M_{diff} = 1.7\%$, $P = 0.333$, 95% CI (−1.9%, 5.3%)]. Although it is not surprising that motion impacted performance, the extent of the decrement is noteworthy.

Another performance measure that is closely related to accuracy but has important implications for training and motion is how many ships were not destroyed by the subject. These data were also submitted to a 2 (Stance) $\times$ 3 (Scenario) ANOVA. There was no main effect of Stance, $F < 1$, but there was a main effect of Scenario [$F(2,38) = 75.28$, $P < 0.001$, $\eta_p^2 = 0.80$]. The interaction did not reach significance [$F(2,38) = 1.46$, $P = 0.245$, $\eta_p^2 = 0.07$]. The main effect of Scenario again shows that people performed better in the No Motion scenario compared to the two motion-based scenarios. On average, 8.5% of the ships made it past the gunner in the No Motion scenarios. However, when the platform was in motion, the number of ships that were not destroyed increased to approximately 58%. Bonferroni corrected pairwise comparisons of the scenarios showed performance was better in No Motion than Scenario 1 [$M_{diff} = 49.0\%$, $P < 0.001$, 95% CI (37.1%, 60.9%)] and better in No Motion than Scenario 2 [$M_{diff} = 49.7\%$, $P < 0.001$, 95% CI (40.2%, 59.3%)] . There was no difference between Scenario 1 and Scenario 2 [$M_{diff} = 7.0\%$, $P = 0.825$, 95% CI (−7.8%, 6.3%)]. This illustrates that the decrease in accuracy due to motion has an even greater operational impact than additional ammunition expended.

DISCUSSION

The present study examined whether postural instability contributed to motion sickness symptoms during an active engagement task with operational relevance. Subjects engaged in a simulation in which they fired at hostile ships while standing on a platform that moved in the same fashion as a rigid hull inflatable boat. While performing this task, subjects' feet were either affixed to the platform (to decrease postural stability) or not (allowing for minor postural adjustments). Results indicated a significant decline in accuracy of shots fired and number of ships disabled due to motion, but there was no significant difference between the stances with respect to motion sickness or performance on the shooting task. The current study demonstrates that postural instability does not account for the level of motion sickness induced by simulated sea-state motion.

Several study limitations should be considered when interpreting these results. First is that there is a lack of a true control condition. Although subjects were able to adjust their stance in the Free condition, they could not anticipate the motion of the platform. They may have been able to adapt to the larger motions but would still need to make smaller adjustments. Thus, in the Free condition, participants could not make every movement necessary to maintain perfect postural stability. Additionally, fixing the feet to the platform has been shown to reduce postural stability, but it does not eliminate it entirely. The bindings make it more difficult to make smaller adjustments to posture (e.g., by engaging the ankles), but these adjustments can still be made. It is quite possible that a different method would be more effective in reducing—or ensuring—postural stability. Thus, subjects were not able to maintain their postural stability perfectly,

Table I. Total and Subscale SSQ Scores; Means (± SE).

	NAUSEA		OCULOMOTOR		DISORIENTATION		TOTAL	
TIME	**FREE**	**FIXED**	**FREE**	**FIXED**	**FREE**	**FIXED**	**FREE**	**FIXED**
Baseline	0.48 (0.48)	2.39 (1.53)	3.03 (1.50)	1.90 (1.33)	1.39 (0.96)	0.70 (0.70)	2.06 (0.96)	3.74 (1.63)
No Motion	1.91 (1.12)	3.82 (1.28)	3.41 (1.50)	1.90 (1.33)	1.39 (0.96)	2.09 (1.14)	2.43 (1.31)	3.37 (1.21)
Scenario 1	8.11 (2.43)	11.45 (2.82)	3.79 (1.51)	4.55 (1.77)	14.62 (5.76)	6.26 (3.27)	8.42 (3.09)	8.98 (2.29)
Scenario 2	14.31 (3.50)	20.03 (3.97)	12.51 (2.92)	8.72 (2.54)	21.58 (6.74)	12.53 (5.14)	14.21 (3.97)	18.89 (3.67)

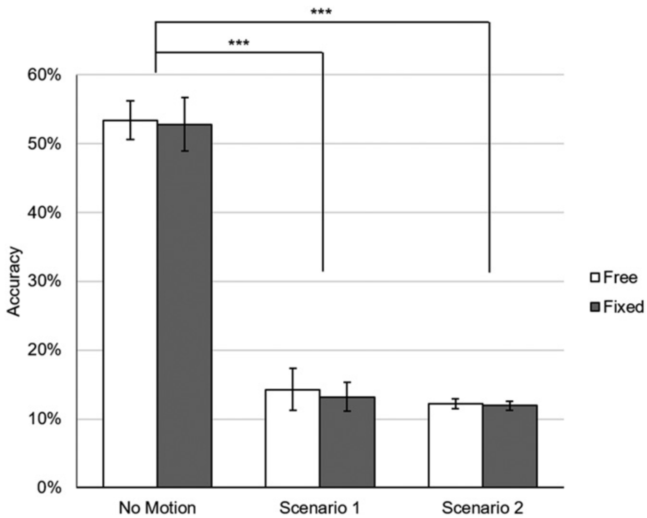

Fig. 3. Accuracy (number of shots on target / total number of shots) for each condition. Error bars represent the standard error of the mean. *** Significant at $P < 0.001$.

which limits the conclusions that can be drawn from these data. Another limitation is that the SSQ scores were relatively low, even after 20 min of exposure. SSQ scores were significantly higher at posttest but were not high enough that subjects would be classified as sick; although, in the Free condition, both the Nausea and Disorientation subscales are above the 85th percentile.[8] A larger sample size may also have helped with this issue. Finally, the shooting task was operationally relevant, but it could have been improved by allowing participants to practice. It is well known that performance improves with practice, and in an operational scenario, it can safely be assumed that the machine gun operator will be well practiced. The participants in the current study were not trained in the use of the weapon, limiting some of the conclusions that can be made regarding the impact of motion on performance.

Although the manipulation has successfully reduced postural stability in the Fixed condition previously, it is possible that the differences between conditions were minimized by the shooting task. The shooting task itself may also have altered expected results despite its operational validity. Previous work has shown that even lightly touching a stationary surface can reduce sway.[6,7] Allowing the subjects to hold onto the weapon while firing almost certainly increased their stability, thus reducing overall motion sickness. However, we do not believe this to be the case. Pettijohn et al.[14] used the same motion profile and Fixed vs. Free manipulation, but subjects were not allowed to hold onto anything while the platform was in motion. A comparison of SSQ scores after the same amount of motion exposure from this experiment and that reported in Pettijohn et al.[14] (20 min) showed that the scores were not significantly different ($F < 1$). This similarity between experiments suggests that holding onto the weapon did not impact symptomology. Likewise, it suggests that the shooting task did not serve to reduce symptoms by taking subjects' minds off their symptoms. It should be noted that this is not a perfect comparison because there may be differences in SSQ due to the use of different VR headsets, and in the current study, there was additional exposure to the headset during the 10-min No Motion profile.

This operational criticism extends into the motion profiles as well, which were chosen for relevance to military operations—specifically naval operations, although the induced motion could be similar to that experienced in a moving vehicle or helicopter. The corresponding MS symptoms might not be considered severe for general MS research, but they represent symptoms as experienced in this operational paradigm. It would be possible to create a more extreme motion profile and induce more severe MS symptoms, but not without calling into question operational validity. For example, it would be reasonable to assess how a pilot recovers from severe motion during a mishap or amidst a crash, but it would not be reasonable to assess marksmanship accuracy of a door gunner while a helicopter is crashing. This example represents an important question in experimental design for military research into MS: does the selected design need to induce motion sickness, or does the selected design need to reflect an operationally-relevant task? Here we chose to explore a more operationally-relevant task, although we do note that this approach does limit theoretical conclusions to less severe motion profiles.

The issue of motion profiles also highlights a variety of experimental design questions not addressed by the current investigation. For example, there are multiple combinations of ship types and sea states that might have differential impacts on either MS symptoms, human performance issues, or some combination of both. The present investigation could only describe symptoms and performance from the assessed combination. Similarly, and especially relevant for naval operations, there is a concern about prior experience with motion profiles. Sailors are almost never naïve personnel in motion-based studies, and their prior experience could further influence the findings in a variety of ways. The operational relationship also provides myriad operational activities that need to be conducted despite the physical motion, to include less severe motion profiles for maintenance activities under normal operations as well as more severe motion profiles for emergency repair or rescue operations. These limitations highlight the need for additional operational research as much as they highlight the limitations of this study. Mixed reality simulations, especially those that include physical motion, remain highly novel outside an aviation context and warrant additional research.

Following from these experimental design questions, the current results do not support PIT as the primary cause of MS. This conclusion comes with several caveats. First, the less extreme motion profile and corresponding MS symptoms limit the conclusion to subtle or moderate symptoms rather than acute symptom profiles. It is possible that PIT differentially explains MS based on symptom severity, where PIT better explains the development of MS for extreme symptoms but not subtle symptoms. The current results can only speak to the subtle end of this spectrum and note that PIT does not appear to be a primary cause of MS under these circumstances. Still, this study is not the first to fail to find a link between postural sway and MS symptoms, which does lend support to these conclusions even if they are contained to the subtle end of a symptom spectrum. Lubeck et al.[11] found increased visually-induced motion sickness following exposure to moving pictures as opposed to still pictures. Importantly, the authors also found that exposure to both image types resulted in similar increases in postural sway. These data suggest that increases in sway, and presumably decreases in stability, are not always accompanied by increased visually-induced motion sickness. An additional analysis between high- and low-score SSQ groups did not find group differences on postural sway measures.[11] Thus, it appears that postural sway and MS symptomology, at least in the case of visually-induced sickness, can be decoupled in some circumstances. For the current findings, this point either supports the idea that PIT is not a primary cause of MS symptoms, or, in the case that multiple mechanisms of symptom induction exist, PIT is not a primary cause of MS symptoms in less extreme motion profiles with subtle MS symptomology. Either position fails to provide strong support in favor of a causal link between PIT and MS symptomology. Other studies have similarly failed to demonstrate a causal link between PIT and MS symptomology, where increasing postural stability resulted in either increased motion sickness or no difference.[25]

ACKNOWLEDGMENTS

The technological concept underlying this study, GunnAR, was developed by Lt. Robert McClenning, a training officer assigned to the guided-missile destroyer USS *Gridley* (DDG 101) and winner of the Office of Naval Research 2016 Innovation Jam, and developed/realized by the Battlespace Exploitation of Mixed Reality (BEMR) laboratory at SSC PAC. The authors would like to thank David Rousseau and Garrison Price for their assistance in setting up the experiment.

The views expressed in this article are those of the authors and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, nor the U.S. Government.

The study protocol was approved by the Naval Medical Research Unit Dayton Institutional Review Board (NAMRUD.2016.0001) in compliance with all applicable federal regulations governing the protection of human subjects.

Financial Disclosure Statement: This research was funded by the Office of Naval Research under work unit number H1515. The authors have no financial or non-financial competing interests in this manuscript.

Authors and affiliations: Kyle A. Pettijohn, Ph.D., Dominick V. Pistone, Andrew L. Warner, B.A., Grant J. Roush, B.A., and Adam T. Biggs, Ph.D., Naval Medical Research Unit Dayton, Wright-Patterson AFB, OH; K. A. Pettijohn, A. L. Warner, and G. J. Roush, The Henry M. Jackson Foundation for the Advancement of Military Medicine, Bethesda, MD; and D. B. Pistone, Oak Ridge Institute for Science and Education, Oak Ridge, TN.

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