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Vertical display oscillation effects on forward vection and simulator sickness

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Abstract
Background: The current study investigated the effects that vertical display oscillation had on the development of both vection and simulator sickness. Methods: Sixteen subjects were exposed to optic flow displays, which simulated either: (i) constant velocity forward self-motion (pure radial flow); or (ii) combined constant velocity forward and vertically oscillating self-motion (radial flow with vertical oscillation at one of three frequencies: 1.8, 3.7 or 7.4 Hz). During each 10-min display exposure, subjects rated the strength of their vection and 8 symptoms listed on the Subjective Symptoms of Motion Sickness (SSMS) scale at 2-min intervals. Subjects also completed the Simulator Sickness Questionnaire (SSQ) designed by Kennedy and colleagues before and after each trial, which generated a total SSQ score and three SSQ sub-scores (nausea, oculomotor symptoms, and disorientation). Results: Vertically oscillating displays (Mean = 5.51; S.D. = 2.5) were found to produce significantly stronger vection ratings than non-oscillating displays (Mean = 3.56; S.D. = 2.1). Vertically oscillating displays (Mean = 58.18; S.D. = 32.2) were also found to produce significantly more severe sickness (as rated by total SSQ scores) than non-oscillating displays (Mean = 29.67; S.D. = 24.7). Both vection and sickness symptoms increased in magnitude with prolonged exposure to optic flow. Conclusions: Our findings appear to represent a special case in visual self-motion perception, where high-frequency vertical oscillation both enhances vection and increases simulator sickness, when it is incorporated into an optic flow display simulating constant velocity self-motion in depth.

Keywords
Vertical, display, oscillation, effects, forward, vection, simulator, sickness

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Vertical Display Oscillation Effects on Forward Vection and Simulator Sickness

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Running head: OSCILLATION EFFECTS ON VECTION AND SIMULATOR SICKNESS

Abstract

Background: The current study investigated the effects that vertical display oscillation had on the development of both vection and simulator sickness. ***Methods:*** Sixteen subjects were exposed to optic flow displays, which simulated either: (i) constant velocity forward self-motion (pure radial flow); or (ii) combined constant velocity forward and vertically oscillating self-motion (radial flow with vertical oscillation at one of three frequencies: 1.8, 3.7 or 7.4 Hz). During each 10-min display exposure, subjects rated the strength of their vection and 8 symptoms listed on the *Subjective Symptoms of Motion Sickness* (SSMS) scale at 2-min intervals. Subjects also completed the Simulator Sickness Questionnaire (SSQ) designed by Kennedy and colleagues before and after each trial, which generated a total SSQ score and three SSQ sub-scores (nausea, oculomotor symptoms, and disorientation). ***Results:*** Vertically oscillating displays (Mean = 5.51; S.D. = 2.5) were found to produce significantly stronger vection ratings than non-oscillating displays (Mean = 3.56; S.D. = 2.1). Vertically oscillating displays (Mean = 58.18; S.D. = 32.2) were also found to produce significantly more severe sickness (as rated by total SSQ scores) than non-oscillating displays (Mean = 29.67; S.D. = 24.7). Both vection and sickness symptoms increased in magnitude with prolonged exposure to optic flow. ***Conclusions:*** Our findings appear to represent a special case in visual self-motion perception, where high-frequency vertical oscillation both enhances vection and increases simulator sickness, when it is incorporated into an optic flow display simulating constant velocity self-motion in depth.

Keywords: self-motion; optic flow; simulator sickness; sensory conflict.

Flight (and other vehicle) simulators are commonly found to induce symptoms of motion sickness (10,11). This simulator sickness differs from other forms of motion sickness (such as airsickness) in that physical motion of the observer is not required. In fixed-base vehicle simulators, individuals commonly experience compelling visual illusions of self-motion, known as vection. It has been often reported that vection precedes the onset of symptoms of simulator sickness (11). However, only a few studies have attempted to directly examine the relationship between these two phenomena. One such study by Hettinger, Berbaum, Kennedy & Dunlap (10) found support for the notion that individuals who experience vection during simulation are more likely to develop simulator sickness. They measured the vection and sickness produced by a fixed-based flight simulator, which simulated repeated banks, turns, and changes in apparent altitude relative to mountainous terrain. While 80% of the subjects who experienced vection during the experiment became sick, only 20% of the subjects who reported “no vection” experienced significant simulator sickness. Another study by Lee, Yoo and Jones (15) examined the relationship between vection and simulator sickness in a driving simulator. As in the above study they treated vection as a dichotomous variable and found that 88% of the subjects who experienced vection also experienced significant sickness, compared to only 50% of the subjects who reported “no vection”. Similarly, other studies have shown that visual field restriction and/or fixation diminished both vection and simulator sickness (optokinetic nystagmus was also reduced) (8,23).

While the above studies have shown that visual displays which produce the strongest vection *can sometimes* produce more severe sickness, Webb and Griffin (24) note that this is not sufficient to demonstrate the existence of a causal relationship between vection and simulator sickness. In their study, they compared the vection and simulator sickness induced by visual motion displays consisting of either a large field of moving dots (i.e. an optic flow pattern) or a single moving dot. While vection was significantly reduced for displays containing only a single dot, sickness did not differ significantly between the two display conditions. Consistent with their findings, a more recent study by Bonato, Bubka and Palmisano (4) also found evidence that not all instances of vection lead to simulator

sickness. This study compared the vection and sickness induced by optic flow patterns that either steadily expanded (simulating forward self-motion) or alternately expanded and contracted (simulating alternating forward and backward self-motions). We found that these alternating displays induced less vection and provoked more severe sickness than the steadily expanding displays and argued that differences in the sensory conflicts generated by these different displays might have been responsible for both effects.

The aim of the current study was to further examine the relationship between vection and simulator sickness. Our stationary observers were shown computer generated displays of either (i) *pure radial flow* – simulating constant velocity forward self-motion; or (ii) *vertically oscillating radial flow* – simulating constant velocity forward self-motion combined with up and down self-accelerations. In the case of the latter, the high-frequency vertical oscillations occurred at either 1.8, 3.7 or 7.4 Hz {note that the head can be subjected to vertical perturbations up to 15 Hz during locomotion (9)}. While definitions of sensory conflict differ (3,22,25), most theories would predict that *pure radial flow* displays should produce less sensory conflict than *vertically oscillating radial flow* displays. For example, according to Zacharias and Young's (25) version of sensory conflict theory, stationary observers should only experience transient visual-vestibular conflict when presented with our *pure radial flow* displays. During a real forward self-motion, vestibular activity fades quickly after the individual has accelerated up to a constant velocity, and thus vestibular activity would only be expected to briefly accompany this type of optic flow. Conversely, stationary observers should experience significant and sustained visual-vestibular conflict when presented with *vertically oscillating radial flow* displays, because: (i) visual self-motion perception is regarded to be primarily sensitive to optic flow patterns with low temporal frequencies (2,20); and (ii) vestibular activity indicating vertical self-oscillation would be expected throughout the trial. Thus, while the current study was exploratory in nature, our initial expectations were that adding vertical display oscillation to our radial flow displays should increase sensory conflict, thereby reducing the vection and increasing simulator sickness compared to non-oscillating radial flow displays.

METHODS

Subjects

Eighteen students at the University of Wollongong voluntarily participated in this experiment for course credit (9 males, 9 females). All were non-pilots and had not previously experienced illusions of self-motion in the laboratory. Their mean age was 24.5 years (S.D. 4.9 years). Subjects fasted for at least 2 hours before each trial. Individuals reporting any visual, vestibular, neurological or gastrointestinal abnormality, or any other health problem, were not allowed to participate. The Wollongong University Ethics Committee approved the study in advance. Each subject provided written informed consent before participating in the study. The data from two subjects was not included because: (i) the male subject did not complete the pre-treatment items for one experimental condition; and (ii) the female subject discontinued the experiment after experiencing above criterion simulator sickness on the first trial (i.e. well-being ratings greater than "5"). Thus, data are reported for only sixteen of these eighteen subjects (8 males, 8 females).

Apparatus

Displays were generated on a Macintosh G4 personal computer and presented on the screen of an Apple Trinitron monitor [resolution was 1024 pixels (horizontal) x 768 pixels (vertical); the update rate was 98 frames per second]. The screen subtended a visual angle of 46° H x 37.5° V when viewed through a viewing tube 50 cm distant. This viewing tube (attached to a head-chin support) blocked the observer's view of their stationary surroundings, including the monitor's frame. During the experiment, verbal ratings were obtained and recorded using two cassette tape recording/playing systems. The first played a pre-recorded tape which prompted the subject for vection, simulator sickness symptoms (SSMS items only) and well-being ratings every 2 minutes. The second recorded both the first tape's promptings and the subject's responses to each.

Displays

The optic flow displays used in the experiment consisted of 400 blue moving filled in squares (3cd/m^2) on a black background (0.03cd/m^2). Each square's velocity and total area (0.16^o-2.42^o) increased as the observer appeared to approach the 3-D cloud. While simulated speed and distance are relative in this type of display, it is helpful to specify these values in real world units. These displays were consistent with the observer traveling at a forward speed of 7 m/s through a cloud of objects which extended 20 m along the depth axis. As the original objects disappeared off the edge of the screen they were replaced by new objects at the opposite end of space (i.e. along the depth axis). These new objects appeared at the same horizontal and vertical starting positions as the originals, so as to maintain a constant display density. While all the visual displays simulated constant velocity forward self-motion (based on the radially expanding component of the optic flow), most also simulated sinusoidally oscillating vertical self-motions. The four vertical oscillation frequencies used were either 0 Hz (i.e. no oscillation control), 1.8 Hz (low frequency), 3.7 (medium frequency) or 7.4 Hz (high frequency). The amplitude of this sinusoidal vertical oscillation was +/-4.5°.

Assessment Instruments

During each trial, vection ratings were obtained every two minutes. These vection strength ratings were measured on a 0-10 scale, with 0 representing "I feel completely stationary" and 10 representing "All of the visual motion is due to my self-motion". In addition to these ratings, we used the following two assessment instruments. The Simulator Sickness Questionnaire (SSQ) was used to measure specific simulator sickness symptoms (nausea, oculomotor symptoms, disorientation) at the beginning and end of the trial and the Subjective Symptoms of Motion Sickness (SMSS) scale was taken at 2 minute intervals to measure the temporal development of simulator sickness over the duration of the trial. The details of each instrument are provided below:

(1) The SSQ specifically assessed the simulator sickness symptoms produced by our four display types (13). When scored according to published guidelines, the SSQ yields four scores: a total SSQ score, a nausea sub-score, an oculomotor sub-score (e.g., eye strain, difficulty focusing), and a disorientation sub-score. Sixteen questionnaire items contribute to these SSQ scores. They are as follows: general discomfort, fatigue, headache, eye strain, difficulty focusing, increased salivation, sweating, nausea, difficulty concentrating, fullness of the head, blurred vision, dizziness with eyes open, dizziness with eyes closed, vertigo, stomach awareness, and burping. For each trial, subjects indicated the degree to which each symptom was experienced pre-treatment and post-treatment by circling one of four choices (0 = “none”, 1 = “slight”, 2 = “moderate”, or 3 = “severe”).

(2) The SSMS scale consists of eight specific symptom questions that are summed to provide an overall measure of simulator sickness (5). The eight symptoms that collectively contribute to the total SSMS score are spinning, dizziness, bodily warmth, headache, increased salivation, stomach awareness, nausea and dry mouth. We used the *total SSMS score* (the sum of the scores for the 8 symptoms) to examine the development of simulator sickness within each trial. At two minute intervals, subjects were requested to rate each of the eight symptoms as follows: 0 = “none”, 1 = “slight”, 2 = “moderate”, or 3 = “severe”. As vection ratings were also obtained at two-minute intervals, total SSMS was an ideal tool for examining the relationship between the onset of vection and the development of simulator sickness.

As a check on the subject’s condition throughout the experiment, overall well-being ratings (0 = “I feel fine” and 10 = “I feel awful as if I am going to vomit”) were obtained every 2 minutes. This wellbeing data has not been included in the analyses below but served as a means of assessing whether or not subjects were well enough to continue in a trial.

Design & Procedure

The briefing for each trial began with a description of the tasks which would be performed prior, during and following exposure to the experimental display. Subjects were told that they would see a display of moving objects and that "sometimes the objects may appear to be moving towards you; other times you may feel as if you are moving. Your tasks are to (when prompted) rate the strength of your feeling of self-motion, your overall wellbeing, and any symptoms of simulator sickness". The details of these three verbal rating scales were then discussed. Subjects were also instructed on how to fill out the written SSQ prior to and following display exposure. Next they completed the first two pages of the SSQ (the general background and pre-treatment scores). The subject was then requested to place his or her head on a chin rest and look at the blank monitor through the viewing tube. The experimenter turned the lights off. Then he simultaneously started the optic flow display and pressed play and record on the two tape recorders. For the next 10 minutes, the subject was then prompted at (2 min intervals) to verbally rate the strength of his or her vection and simulator sickness symptoms (SSMS scale). At the completion of the trial, the display went blank and the lights were switched on. The subject immediately completed the post exposure section of the SSQ and then rested until the severity of symptoms subsided. Subjects ran over eight days, with trials being separated by approximately 24 hours, which allowed the residual simulator sickness symptoms from the previous trial to subside. Each subject was exposed twice to the four different *display types* (i.e. 8 trials in total per subject). In order to control for possible order effects, the experimental displays were presented in a different random order for each subject and performance in identical conditions was averaged.

RESULTS

Separate repeated measures ANOVAs were performed on the vection rating and the total SSMS score data. After stimulus onset, both vection ratings and SSMS symptoms were

collected at 2-minute intervals until the trial ended. Thus, the factors examined in these ANOVAs were *display type* (0 Hz, 1.8 Hz, 3.7 Hz or 7.4 Hz oscillation) and *exposure time* (2, 4, 6 or 8 minutes). Separate repeated measures ANOVAs were also performed on the 4 SSQ scores (total SSQ, nausea, oculomotor and disorientation). As these data were difference scores (scores post exposure minus scores before exposure), the only factor examined in these analyses was *display type*. We also performed regression analyses on the above measures to determine the degree and direction of the linear relationship between: (i) vection ratings and total SSMS scores; (ii) vection ratings and total SSQ scores; and (iii) total SSMS scores and total SSQ scores.

A. Vection Strength Ratings. We found a significant main effect of *display type* on vection strength ratings [$F(3,45) = 5.16$, $p < 0.004$]. Bonferroni-corrected post-hoc contrasts revealed that: (i) vertically oscillating displays (1.8 Hz – 7.4 Hz) produced significantly stronger vection than the non-oscillating controls (0 Hz) ($p < 0.05$); (ii) the vection produced by 3.7 Hz oscillation was not significantly different from that produced by 1.8 Hz oscillation ($p > 0.05$); and (iii) the vection produced by 7.4 Hz oscillation was not significantly different from that produced by either 1.8 Hz oscillation ($p > 0.05$) or by 3.7 Hz oscillation ($p > 0.05$). We also found a significant main effect of *exposure time* [$F(3,45) = 35.21$, $p < 0.0001$] and a significant interaction between *display type* and *exposure time* [$F(9,135) = 35.21$, $p < 0.0001$]. We interpreted these effects as follows: while the vection strength ratings for all 4 display types increased significantly with the exposure time (2 – 8 minutes), this increase was greatest for the non-oscillating controls (possibly because the vection ratings for oscillating displays were approaching ceiling levels).

[Figure 1 about here]

B. Total SSMS Scores. As expected, we found a significant main effect of *display type* on the total SSMS scores [$F(3,45) = 7.06$, $p < 0.005$]. Bonferroni-corrected post-hoc contrasts

revealed that oscillating displays (1.8 Hz – 7.4 Hz) produced significantly more sickness than the non-oscillating controls (0 Hz) ($p < 0.05$) and that the sickness induced by 7.4 Hz oscillation was significantly greater than that produced by 1.8 Hz oscillation ($p < 0.05$). However, the sickness produced by 3.7 Hz oscillation was not found to be significantly different from that produced by 1.8 Hz oscillation ($p > 0.05$). Similarly, the sickness produced by 7.4 Hz oscillation was not found to be significantly different from that produced by 3.7 Hz oscillation ($p > 0.05$). We also found a significant main effect of *exposure time* [$F(3,45) = 42.78$, $p < 0.0001$], indicating simulator sickness for all 4 display types increased significantly with the exposure time (2 – 8 minutes). However, unlike the vection data, we did not find a significant interaction between *display type* and *exposure time* for the total SSMS data [$F(9,135) = 1.64$, $p > 0.05$].

[Figure 2 about here]

C. SSQ Scores. Four SSQ scores were calculated for each subject using methods and weighting factors outlined in Kennedy et al. (11): a total SSQ score and three sub-scores (nausea, oculomotor symptoms, and disorientation). We found significant main effects of *display type* on the total SSQ data [$F(3,42) = 6.29$, $p < 0.001$], the oculomotor sub-scores [$F(3,42) = 6.25$, $p < 0.001$], the nausea sub-scores [$F(3,42) = 4.44$, $p < 0.009$], and the disorientation sub-scores [$F(3,42) = 5.92$, $p < 0.002$]. Bonferroni-corrected post-hoc contrasts revealed that oscillating displays produced significantly higher ratings than non-oscillating controls on all four SSQ scores ($p < 0.05$ for total, oculomotor symptoms, nausea and disorientation). While these contrasts also revealed that sickness symptoms were not significantly different for 7.4 and 3.7 Hz oscillation conditions ($p > 0.05$), these two oscillation conditions were found to produce significantly greater total SSQ, nausea and oculomotor symptom scores than the 1.8 Hz oscillation condition ($p < 0.05$).

[Figure 3 about here]

D. Relationships between Vection, total SSMS and total SSQ Scores. As the experiment had a repeated measures design, regression analyses were performed on data averaged across the 4 display type conditions. These indicated that: (i) 27% of the variance in total SSQ scores could be explained by the final vection strength ratings [$R^2 = 0.27$, $F(1,14) = 4.76$, $p < 0.05$]; and (ii) 28% of the variance in final SSMS scores could be explained by the final vection strength ratings [$R^2 = 0.28$, $F(1,14) = 5.03$, $p < 0.05$]. These findings clearly indicate that while vection was significantly related to simulator sickness symptoms (as indexed by the SSMS and SSQ) in the present experiment, it was not the only determining factor. As expected, the regression analyses also revealed that 46% of the variance in SSQ scores could be explained by the final SMSS scores [$R^2 = 0.46$, $F(1,14) = 10.64$, $p < 0.006$]. Pearson correlations between vection and total SSMS ratings were also investigated *within each of the 4 display type conditions*. While we did not find a significant correlation between final vection and final SSMS ratings for non-oscillating displays ($r = 0.286$, $p > 0.05$), we did find a significant correlation between vection and SSMS for displays oscillating at 1.8 Hz ($r = 0.691$, $p < 0.05$). However, correlations between final vection and final SSMS ratings did not reach significance for displays with higher frequency oscillations ($r = 0.206$, $p > 0.05$; $r = 0.182$, $p > 0.05$ for 3.7 and 7.4 Hz conditions respectively}.

DISCUSSION

As we predicted, vertically oscillating radial flow displays were found to produce more simulator sickness than non-oscillating radial flow displays, with the higher frequency (7.4 Hz) oscillations producing significantly greater sickness than the lower frequency (1.8 Hz) oscillations. However, contrary to our initial predictions, all three of our vertically oscillating displays (1.8 – 7.4 Hz) were found to significantly increase vection strength (compared to the non-oscillating displays), and this vection advantage was similar for all of the oscillation frequency conditions we tested.

The above oscillation effects on vection appear to conflict with much of the previous vection literature, which appears to show that visual self-motion perception is most effectively stimulated by display oscillations below 1 Hz (2,20,21). However, we note that our oscillation effects on vection are similar to the findings of several recent studies. First, Palmisano and colleagues (17-19) have shown that vection can be increased by adding simulated random horizontal/vertical viewpoint jitter (1-15 Hz – the result is similar to the effects of "camera shake") to displays simulating constant velocity self-motion in depth. Second, Kitazaki and Hashimoto (14) have shown that vection can be increased by adding (0.96 Hz) vertical oscillation to displays simulating constant velocity self-motion in depth. Taken together, these past and present findings may well indicate a special case of self-motion perception, where high-frequency horizontal/vertical perturbations enhance (rather than impair) vection, but only when they are superimposed on a visual display simulating constant velocity self-motion in depth.

Given that the visual display sizes used in the current study were centrally-located and relatively small (46° H x 37.5° V) there is also the distinct possibility that our finding of a high-frequency-oscillation-based advantage for vection might be a property of central (as opposed to peripheral) vision. Contrary to the notion of "peripheral dominance" for vection (6), Andersen and Braunstein (1) showed that vection could be induced in central vision with display sizes as small as 7.5° of visual angle. However, recent research has suggested that the optimal stimuli for vection might differ for central and peripheral vision. In one such study on circular vection, Palmisano and Gillam (16) found evidence that the vection induced in central vision was specialised for higher spatial/temporal frequency optic flow than the vection induced in peripheral vision. Thus, another way to reconcile our findings of high frequency oscillation improving vection with previous data suggesting it should impair vection, is to propose that vection in central vision is specialized for higher frequency oscillation than vection in peripheral vision. While Kitazaki and Hashimoto (14) have recently reported a vertical display oscillation advantage for vection with much larger radial flow

displays (91° H x 76° V), this finding might still have been driven by central vision. The possibility remains that this high frequency simulated oscillation of the viewpoint would have markedly different effects if the displays were only presented to peripheral vision (which is known to be most effectively stimulated by lower spatial and temporal frequency motions).

The present study revealed a modest, positive relationship between vection and simulator sickness, as indexed by both the SSMS and the SSQ. As noted above, 27% to 28% of the variance in simulator sickness could be explained by vection strength ratings. Two factors – the presence/absence of oscillation and exposure time - appeared to underlie this relationship. In terms of the former factor, the increase in both vection and simulator sickness with display oscillation, we had predicted that the addition of oscillation to our visual displays would increase sensory conflict and thus increase simulator sickness. Above we have outlined several reasons why this added display oscillation might also have increased vection - thus contributing to the modest positive correlation between vection and simulator sickness. In terms of the latter factor, the increase in both vection and simulator sickness with exposure time, it should be noted that it took up to 4-6 minutes to reach peak vection in our study. This time course appears quite different from that reported in previous studies (2,6,20), where vection saturation has been shown to occur before 100 seconds exposure to optic flow.

Since only 27-28% of the variance in simulator sickness could be predicted by vection strength ratings, it is clear that other factors must have also been contributing to simulator sickness in the present experiment. Interestingly, our results indicate that the relationship between experienced vection and sickness is strongest when the display's vertical oscillation frequency is the closest to levels typically found during walking (1.4-2.5 Hz) (12). This suggests that the relationship between vection and simulator sickness might be mediated by self-motion experience. Importantly, visually induced eye-movements have also been identified as potential contributors to simulator sickness (7,8,24). Since subjects viewed oscillating and non-oscillating displays without a fixation point to stabilize their gaze

direction, future research should aim to determine the contribution of eye-movements to the vection and simulator sickness induced by such displays.

In general, vection tends to be induced when there is less sensory conflict and motion sickness tends to arise when there is greater sensory conflict. However, the modest positive correlation observed between vection and simulator sickness in the present study suggests that sensory conflict per se is not a unifying explanation for all types of vection and motion sickness**.** We conclude that our current findings may represent a special case of visual self-motion perception, where high-frequency visual oscillations act to enhance vection and increase simulator sickness, when they are superimposed on a radial flow pattern indicating self-motion in depth at a constant velocity.

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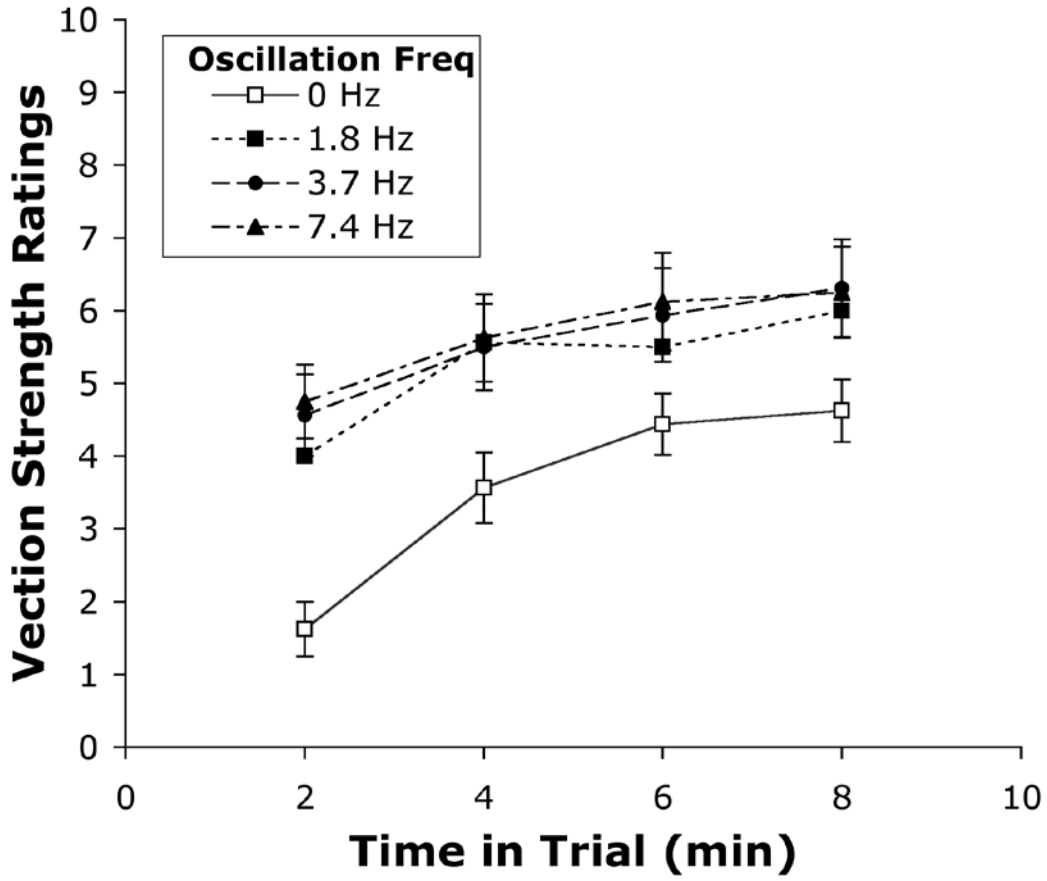

Figure 1. The mean vection strength ratings obtained for the four display types (0 Hz, 1.8 Hz, 3.7 Hz and 7.4 Hz oscillation). Ratings were obtained every 2 minutes (2, 4, 6 and 8 minutes). Error bars represent the standard errors of the means.

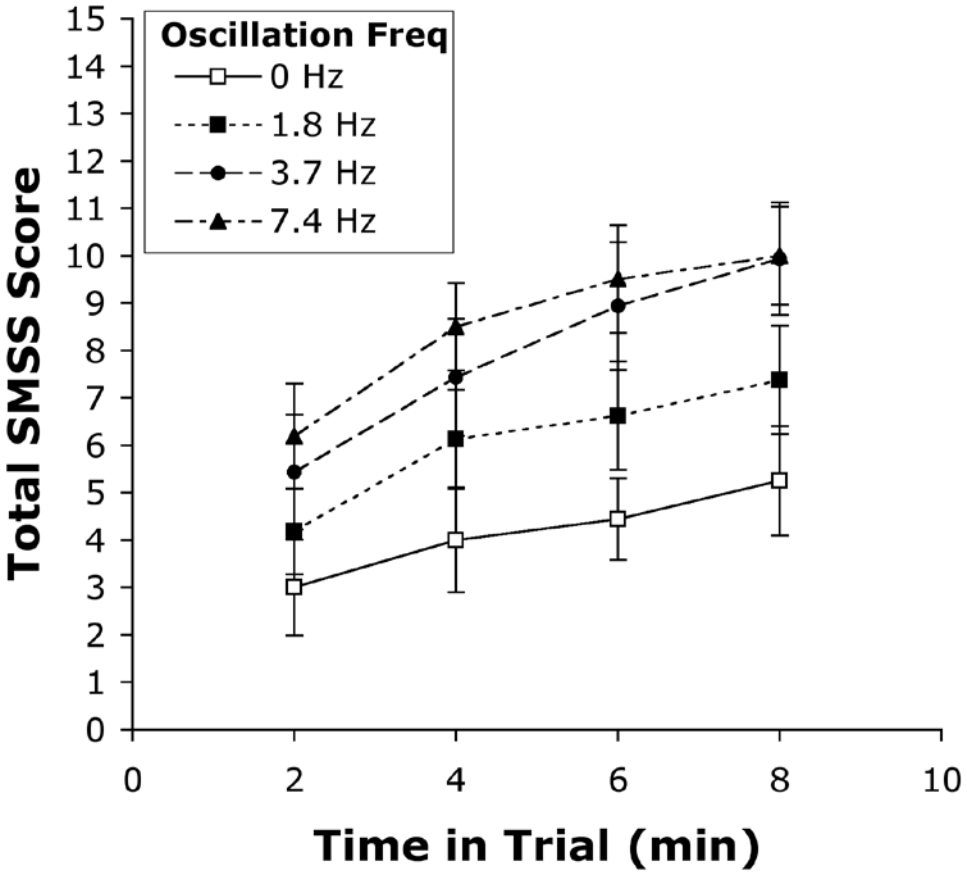

Figure 2. The mean total SSMS ratings obtained for the four display types (0 Hz, 1.8 Hz, 3.7 Hz and 7.4 Hz oscillation). Ratings were obtained every 2 minutes (2, 4, 6 and 8 minutes). Error bars represent the standard errors of the means.

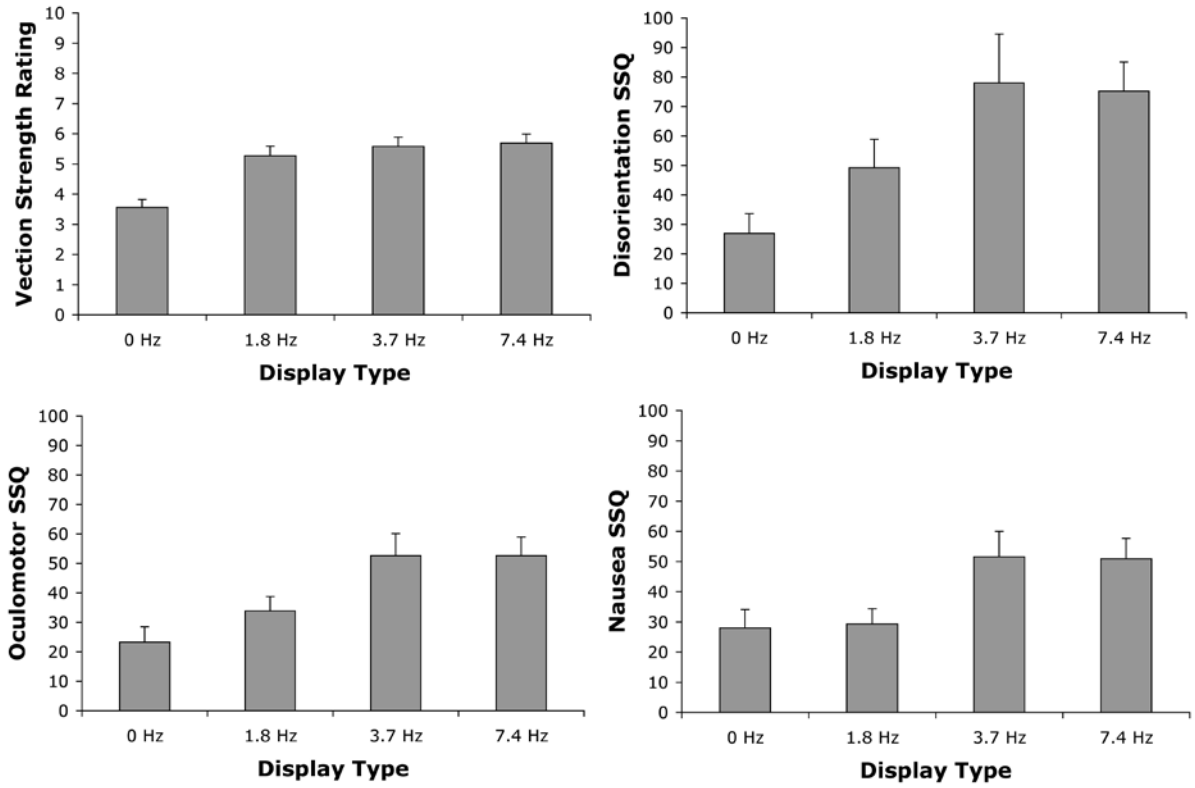

Figure 3. The mean vection strength and SSQ subscores (oculomotor symptoms, nausea and disorientation) obtained following the four display types (0 Hz, 1.8 Hz, 3.7 Hz and 7.4 Hz oscillation). Error bars represent the standard errors of the means.