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Visually induced motion sickness when viewing visual oscillations of different frequencies along the fore-and-aft axis: keeping velocity versus amplitude constant

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ABSTRACT

Exposure to visual oscillations (VOs) can lead to visually induced motion sickness (VIMS). The level of VIMS among viewers has been shown to vary when the frequency of the VOs is changed either by manipulating their amplitude or velocity. The present study investigates whether the level of VIMS would change if we keep the root mean square (rms) velocity or amplitude of VOs constant while manipulating the VO frequency. A total of 25 individuals were exposed to random-dot and checkerboard VOs along the fore-and-aft axis in two experiments. Changing the amplitude (or frequency) of VOs while keeping the rms velocity constant did not affect the level of VIMS; however, increasing the rms velocity (or frequency) of VOs while keeping the amplitude constant made VIMS significantly worse.

Practitioner Summary: Exposure to VOs of the same frequency can cause different levels of nausea depending on the combination of oscillation amplitude and velocity. Results suggest an opportunity for game designers to reduce symptoms of game sickness by using the correct combinations of velocity and amplitude of the visual motions.

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KEYWORDS
Visually induced motion sickness; visual oscillations; frequency responses; control of velocity and amplitude; fore-and-aft axis

1. Introduction

Motion sickness is common in passengers and has been affecting around one-third of the UK and Hong Kong populations (So, Finney, and Goonetilleke 1999; Turner and Griffin 1999). This unpleasant experience nevertheless does not exclusively affect people on the move. A person staying still may also report signs of motion sickness when he or she is exposed to visual environments that give rise to a perception of self-motion (known as *vection*; Hettinger et al. 1990; Reason 1978). In this case, the motion sickness-like symptoms are often referred to as visually induced motion sickness (VIMS) – a term describing a specific type of motion sickness felt by viewers who are exposed to visual motion cues in the absence of physical movement. Symptoms of VIMS mainly include nausea and eye fatigue and have been shown to impair user experience and performance of visual tasks (Caroux, Le Bigot, and Vibert 2013; Read and Bohr 2014).

While the frequency responses of motion sickness in physical motion have long been standardised and used to predict incidence of motion sickness since as early as 1987 (British Standard 6841 1987), the frequency responses of VIMS have received little attention until recently. Duh et al. (2004) hypothesised that visual stimuli that oscillated at around 0.06 Hz were most likely to provoke VIMS. This frequency was later confirmed by Lin and Donald (2005) and Groen and Bos (2008). Yet others have argued that VIMS peaks with visual oscillations (VOs) at 0.1 Hz (Yokota et al. 2005), 0.2 Hz (Diels and Howarth 2012), and even 0.3–2.5 Hz (Kiryu et al. 2008). This discrepancy could be due to the differences in the VOs used in these studies. The frequency responses of VIMS could differ depending on the scene content, movement axis, and/or the velocity and amplitude. In previous motion sickness studies involving physical motions (e.g. seasickness: Griffin 1996), effects of motion accelerations were studied because our vestibular organs are sensitive to accelerations. With VIMS, however, evidence has been reported that human visual systems are more sensitive to the velocity than the acceleration of VOs (Schrater, Knill, and Simoncelli 2000; Schaffer and Durgin 2005). Furthermore, the study of visual motion velocity is consistent with the 'spatial velocity' hypothesis proposed by So, Ho, and Lo (2001), which predicts that VIMS is correlated with the velocity of contrasting spatial patterns projected on the human retina. In a VIMS study, the temporal frequency of a VO can be manipulated in two ways: (i) by keeping the root mean square (rms) velocity of the VO constant but changing the amplitude; or (ii) by keeping the amplitude of the VO constant but changing the rms velocity. Table 1 summarises the findings and parameters of VOs in past studies of the frequency responses of VIMS. While the effects of scene content (So, Ho, and Lo 2001), motion axis

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Table 1. Past studies of frequency responses of VIMS: findings and particulars of VOs used.

Citation	Frequency at which VIMS peaks (Hz)	Scene of VOs	Axis of VOs	Control of amplitude and velocity
Duh et al. (2004)	0.06	Vertical black-and-white (B/W) stripes	Yaw (with yaw physical motion)	Constant velocity
Lin and Donald (2005)	0.08	Virtual environments (VEs) in driving simulators	Roll and navigation	Constant amplitude
Groen and Bos (2008)	0.08	VEs in driving simulators	Lateral and navigation (with weak multi-axis physical motion)	Uncontrolled
Yokota et al. (2005)	0.1	Virtual living room	Roll	Constant amplitude
Diels and Howarth (2012)	0.2	Star field	Fore-and-aft	Constant velocity
Kiryu et al. (2008)	Between 0.3 and 2.5	Recorded videos of bike ride	Multiple axes	Mixed and uncontrolled

(Lo and So 2001) and latency (Kinsella et al. 2015) on the frequency responses of VIMS have been studied previously, the effects of velocity and the interacting effects between velocity and frequency (hence amplitude) on the frequency responses of VIMS have not been investigated. This study was hence designed to fill this gap.

In this paper, two experiments are reported. In the first experiment, we tested the hypothesis that manipulating the velocity of VOs and manipulating the amplitude of VOs would give different VIMS frequency responses. Because the severity of VIMS can be affected by the complexity of visual motion scene (Lo and So 1999), in the second experiment we extended certain conditions of the first experiment to a different but also commonly studied scene to test the generalisability of our findings. In both experiments, we exposed participants to continuous VOs along the fore-and-aft axis. We used the fore-and-aft axis because when navigating in virtual environments (e.g. flight/car simulators; combat/action games), forward and backward are inevitably the most frequent directions of motion. Among existing studies, only Diels and Howarth (2012) have studied the frequency responses of VIMS along the fore-and-aft axis without mixing up with other axes (see Table 1). We adopted their VO pattern (i.e. a star field, Figure 1(a)) in our first experiment. In the second experiment, we used a radial striped black-and-white checkerboard pattern (see Figure 1(b)). Black-and-white striped patterns are commonly used in VIMS studies (e.g. Ji, So, and Cheung 2009; Guo et al. 2012). Postural sway measurements were added in the second experiment because Riccio and Stoffregen (1991) suggest that the postural sway could also be a valid measure of VIMS. Bos et al. (2013) reported that low-frequency postural instability was observed after watching a 3D aviation documentary in a cinema. Some of the preliminary findings from the second experiment have been presented at a conference (Chen et al. 2012).

2. Methods of Experiment 1

All reported experiments were approved by the human subject committee at the Hong Kong University of Science and Technology. Written consents were obtained from all participants. A within-subject design was adopted for both experiments. To reduce the effects of adaptation, participants were given a 7-day rest on average between trials.

2.1. Participants

Thirteen healthy university students (seven females) aged between 18 and 25 years participated in this experiment. All participants had normal or corrected-to-normal vision, intact vestibular function and were not on any medication. They showed 20/20 visual acuity in both near and far fields in our screening test. As Webb and Griffin (2002) reported that visual acuity can affect VIMS levels, we controlled for this factor in our study. We asked the participants to fill out a Motion Sickness Susceptibility Questionnaire (MSSQ). The average percentile score was 49.8%, which indicates that the sample was representative of the general population in terms of susceptibility (Golding 1998).

2.2. Apparatus and stimulus

Experiment 1 used star-field VOs along the fore-and-aft axis. The participants were asked to sit in a chair (complete with backrest) fixed at a distance of 1.1 m away from a cylindrical projector screen in a dark room. They then rested their heads on a chin-rest to limit their head movements (see Figure 1(a)). Each participant wore a pair of custom-made goggles that restricted their visual field to approximately 60° × 50° and occluded any visual references (the floor, screen edges, etc.).

The VOs were similar to those used by Diels and Howarth (2012). They consisted of 500 white filled-in circles (100 cd/m^2) moving randomly in all directions against a dark background (1.07 cd/m^2). The VOs were produced using the COGENT^{TM} Graphics Toolbox embedded in Matlab (version 6) with a resolution of 1280 × 1024 pixels at 60 frames per second. The circles on the display were programmed to move in such a way that geometrically mapped to perspective motion along the fore-and-aft axis. The simulated visual motion was sinusoidal. A red dot subtending a visual angle of 0.5° was shown at the centre of the display. Participants were instructed to fixate on the red dot as the circles moved (normal blinking was permitted). All VOs were projected on a screen in front of the participants. Thus, unlike a typical helmet-mounted display

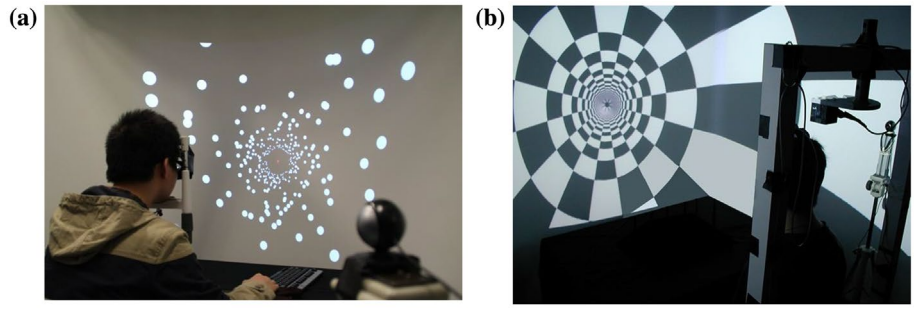

Figure 1. The experimental set-ups and stimuli: (a) Experiment 1 used the star-field VOs; (b) Experiment 2 used the radial-striped checkerboard VOs.

Table 2. Details of visual motion parameters (i.e. frequency, rms velocity and amplitude) for the 17 conditions in Experiment 1.

Cond #	Freq (Hz)	rms Vel (m/s)	Amp (m)	Cond #	Freq (Hz)	rms Vel (m/s)	Amp (m)
1	0.2	88.9	100	10	0.8	22.2	6.25
2	0.05	22.2	100	11	3.2	88.9	6.25
3	0.4	22.2	12.5	12	0.2	5.6	6.25
4	0.1	11.1	25	13	0.1	22.2	50
5	0.0125	5.6	100	14	0.05	88.9	400
6	0.4	44.4	25	15	0.05	1.5	6.25
7	0.2	22.2	25	16	0.8	356	100
8	0.8	88.9	25	17	0.8	5.6	1.56
9	0.05	5.6	25				

system, there was no added time delay between the presentation of the VOs and the head movements of the participants.

2.3. Experimental design

In order to investigate the interacting effects of velocity and amplitude on the frequency responses of VIMS, 17 combinations of rms velocity, amplitude and frequency were studied (see Table 2). These combinations covered three levels of constant rms velocity (5.6, 22, 89 m/s), three levels of constant amplitude (6.25, 25, 100 m) and four-to-five levels of frequency ranging from 0.0125 to 3.2 Hz. At each level of constant velocity or amplitude, a frequency response curve of VIMS was measured. All participants took part in all conditions and the experiment lasted about six months as a 7-day rest period was allowed between exposure trials to reduce the effect of adaptation.

2.4. Procedures and measurements

The order of exposure to the 17 conditions was randomised. Each trial lasted for 30 min. At 5-min intervals, the participants were asked to verbally rate their sensation of nausea. Nausea was measured on a 7-point Likert scale adopted from Golding and Kerguelen (1992; 0 – *no symptom*, 1 – *any slight symptom*, 2 – *mild symptoms but no nausea*, 3 – *mild nausea*, 4 – *mild to moderate nausea*, 5 – *moderate nausea but can continue* and 6 – *moderate nausea and want to stop*). A trial was terminated when a nausea level of 6 was reached or at the end of the 30-min period, whichever came sooner. The nausea ratings for the rest of the trial were assigned a value of 6 if a trial was terminated before 30 min was up.

Before and after exposure, participants completed a simulator sickness questionnaire (SSQ; Kennedy et al. 1993). The pre-exposure SSQ was administered to ensure that the participants were all free from symptoms at the beginning of the experiment. None of the participants reported more than one slight symptom among the 29. A CCTV camera was set up to monitor participants' compliance with the instructions.

3. Results of Experiment 1

Non-parametric statistical methods were used throughout in view of the non-Gaussian nature of the experimental data collected in this study (Shapiro–Wilk test, $p < 0.05$). For consistency with the non-parametric analyses, medians rather than means are reported in the figures. More specifically, the Friedman repeated-measures analysis of variance by ranks and Wilcoxon matched-pairs signed ranks tests were used. The data were analysed using the software package *IBM SPSS Statistics 21*.

3.1. Nausea ratings

Participants reported ratings of nausea at 5-min intervals during each 30-min exposure period. The median nausea ratings collected at the end of the 30-min period were plotted against the frequencies of VOs and grouped into two categories: (a) constant rms velocity and (b) constant amplitude (Figure 2). Each category contained three frequency response curves corresponding to different levels of velocity or amplitude.

When rms velocity was kept constant at 5.6 or 89 m/s, frequency did not affect the levels of nausea significantly ($p > 0.2$, Friedman test). At 22 m/s constant rms velocity, nausea ratings increased significantly from 0 to 1 when the frequency of VOs was increased from 0.05 to 0.1 Hz ($p < 0.02$, $Z = -2.484$, Wilcoxon signed-rank test). After that, the nausea ratings did not change even when the frequency was further increased to 0.2, 0.4 and 0.8 Hz. On the other hand, when the amplitude of VOs was kept constant at 6.25 or 100 m, results of Friedman tests showed significant effects of frequency on levels of nausea (6.25 m: $\chi^2 = 9.036$, $p < 0.05$;

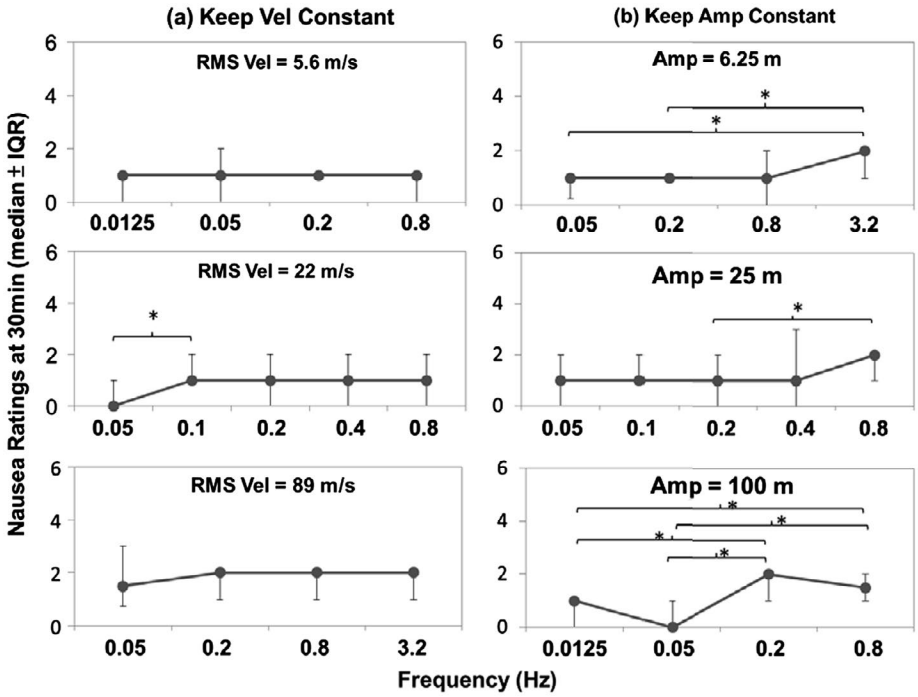

Figure 2. The frequency responses of the nausea ratings (median with inter-quartile range, IQR) for the 13 participants in Experiment 1 where they viewed VOs with (a) constant rms velocities of 5.6, 22 and 89 m/s; or (b) constant amplitudes of 6.25, 25 and 100 m.
Note: Wilcoxon signed-rank, $p < 0.05$.

100 m: $\chi^2 = 18.118$, $p < 0.001$, respectively). Results of Wilcoxon tests indicated that nausea ratings increased with increasing frequency (Wilcoxon, $p < 0.05$, see Figure 2) when the amplitude was kept constant at 25 m. Specifically, the median ratings significantly increased from 1 to 2 when the frequency increased from 0.2 to 0.8 Hz ($p < 0.05$, Wilcoxon).

3.2. SSQ scores

Before and after each trial, participants were required to fill out an SSQ. As indicated in Figure 3, increases in frequency resulted in a significant increase in SSQ total scores when the amplitude was kept constant at 100 m (Friedman, $\chi^2 = 8.791$, $p < 0.05$). In particular, at both 0.2 Hz and 0.8 Hz, the SSQ total scores were significantly higher than those at 0.0125 Hz (Wilcoxon, $Z = -2.673$, $p < 0.01$; $Z = -2.006$, $p < 0.05$, respectively). Paired comparisons also showed that when amplitude was kept constant at 6.25 m, the SSQ total scores at 3.2 Hz were significantly higher than those at 0.8 Hz ($Z = -2.608$, $p < 0.01$, Wilcoxon). The sub-scores (Nausea, Oculomotor, and Disorientation) showed similar patterns as the SSQ total scores.

4. Methods of Experiment 2

4.1. Objective of Experiment 2

In Experiment 1, the frequency of VOs did not have a significant effect on nausea ratings when the velocity of VOs was kept constant at 5.6 and 89 m/s. This is surprising as previous study suggests that nausea levels should peak at 0.2 Hz (Diels and Howarth 2012). In Experiment 2, a different stimulus was used with larger field-of-view. The objective is to verify the results of Experiment 1 with a different and stronger stimulus.

4.2. Participants

Twelve healthy university students (five males) aged between 19 and 24 years participated in this experiment. These students had not participated in Experiment 1. Their susceptibility was measured using the MSSQ and a mean percentile score of 62% was found, which indicates that the sample was slightly more susceptible than the general population (Golding 1998).

4.3. Apparatus and stimulus

Experiment 2 was conducted in the same laboratory as Experiment 1 but a different pattern of VO was used (see Figure 1(b)). The VO was a perspective view from a virtual camera moving inside a long circular tunnel 2000 m in length and having a radius of 5 m (3D Studio Max™). The inside of the tunnel was painted with 50 pairs of black-and-white adjacent sections evenly distributed along the 2000 m tunnel. The perspective view appeared as eight pairs of radial black-and-white stripes (see Figure 1(b)). Luminance of the projected white circular stripes was about 130 cd/m^2 and that of the projected black circular stripes was about 18 cd/m^2, respectively,

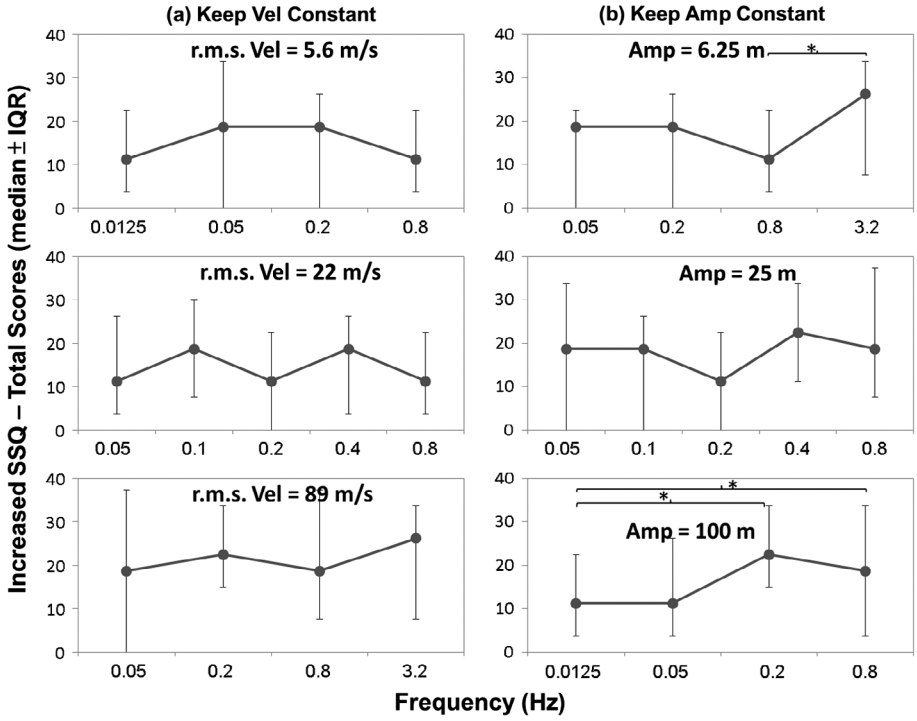

Figure 3. The frequency responses of the SSQ total scores (median with inter-quartile range, IQR) for the 13 participants in Experiment 1 where they viewed VOs with (a) constant rms velocities of 5.6, 22 and 89 m/s; or (b) constant amplitudes of 6.25, 25 and 100 m.
Note: Wilcoxon signed-rank, $p < 0.05$.

on the screen. The tunnel oscillated back and forth along the fore-and-aft axis in a sinusoidal profile giving an illusion for moving forward and backward inside the tunnel. While normal blinking was allowed, the participants were asked to fixate on the centre of the image where there was a black dot subtending an angle of 1.04°. The VOs were projected onto the screen with a field of view of 200° (h) × 50° (v).

4.4. Experimental design

Five different VO frequencies were studied (0, 0.05, 0.1, 0.2 and 0.8 Hz). 0 Hz means a stationary visual scene and was used as a control condition. Each participant was exposed to all five conditions in a randomised order. The rms velocity of the VOs was kept constant at 44.5 m/s, which means the participants visually 'passed through' about one pair of black-and-white stripes per second (Figure 1(b)).

4.5. Procedures and measurements

The procedures were similar to those in Experiment 1 except that the participants stood in front of the screen so that their postural sway could be measured using an electromagnetic receiver fixed to the top of an acoustic headset worn by the participants, see Figure 1(b) (Polhemus 3 Space System, Polhemus Inc., USA). In addition, rated vection was measured on a 7-point rating scale adopted from Webb and Griffin (2002). The scale ranged from 0 ('I perceive that the only thing moving is the visual stimulus and I remain stationary') to 6 ('I perceive that the visual stimulus is stationary, and a strong feeling that I am moving').

5. Results of Experiment 2

5.1. Nausea ratings

The nausea ratings at the end of the 30-min period of the 12 participants are plotted in Figure 4. Partial preliminary results for the first seven participants presented at a conference (Chen et al. 2012). Frequency had a significant effect under all five conditions (0, 0.05, 0.1, 0.2 and 0.8 Hz; Friedman, $\chi^2 = 18.307$, $p < 0.001$). After excluding the control condition of 0 Hz (stationary), however, the effects of frequency were no longer significant ($\chi^2 = 3.606$, $p > 0.3$). This finding is consistent with that of Experiment 1.

5.2. SSQ scores

As shown in Figure 5, results of Wilcoxon signed-rank tests revealed that the difference between pre- and post-exposure SSQ total scores was significantly lower with VOs at 0 Hz than with VOs at 0.2 Hz ($Z = -2.527$, $p < 0.02$) or 0.05 Hz ($Z = -1.965$, $p < 0.05$). Nausea sub-scores were significantly lower at 0 Hz than at 0.8 Hz ($Z = -2.410$, $p < 0.05$) or 0.05 Hz ($Z = -2.489$, $p < 0.05$). No other significant results were found. In particular, no significant differences were found among the 0.05, 0.1,

0.2 and 0.8 Hz conditions for all the SSQ sub-scores and SSQ total scores.

5.3. Vection ratings

Frequency had significant main effects on the vection ratings reported at the end of the 30-min exposure (Friedman, $\chi^2 = 31.284$, $p < 0.01$; Figure 6). After removing the control condition, the significant effects of frequency remained. In particular, vection ratings were significantly lower at 0.8 Hz than at 0.2 Hz (Wilcoxon signed-rank test, $Z = -2.352$, $p = 0.019$), 0.1 Hz ($Z = -2.116$, $p = 0.034$), and 0.05 Hz ($Z = -2.446$, $p = 0.014$). In other words, as the frequency of VOs increased from 0.2 to 0.8 Hz with constant velocity, the median rated levels of vection among viewers of the VOs reduced from 4 to 2.

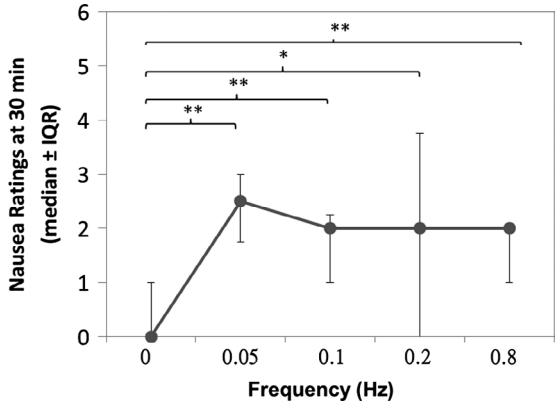

Figure 4. The frequency responses of the nausea ratings at the end of the 30-min exposure for the 12 participants in Experiment 2 (some of the preliminary data from the first seven participants have been presented at a conference (Chen et al. 2012).
Notes: *Sig. different from other conditions, Wilcoxon signed-rank, $p < 0.05$. **$p < 0.01$.

5.4. Postural sway

For each participant, the rms postural sway over the entire 30-min exposure was normalised by dividing the rms sway measured under the moving conditions (i.e. 0.05–0.8 Hz) by those measured under the static condition (0 Hz) (Figure 7). Postural sway (rms) showed a decreasing trend with increasing frequencies. In particular, the normalised rms postural sway at 0.8 Hz was significantly smaller than those at 0.05 and 0.1 Hz (Wilcoxon, $Z = -2.432$, $p < 0.02$; $Z = -2.670$, $p < 0.01$; respectively).

6. Discussion

In this study, we have verified the hypothesis that keeping the rms velocity or amplitude of VOs constant has a significant effect on the frequency responses of VIMS among viewers of the VOs. Results of nausea ratings and SSQ scores consistently suggested two different types of VIMS frequency response. In particular, when rms velocity was held constant (i.e. effects of amplitude were confounded with effects of frequency), VIMS levels were not significantly affected by changes in frequency (Type A). However, when amplitude was held constant (i.e. effects of velocity were confounded with effects of frequency), VIMS levels increased with increasing frequency up to 0.2, 0.8 and 3.2 Hz depending on the amplitude (Type B).

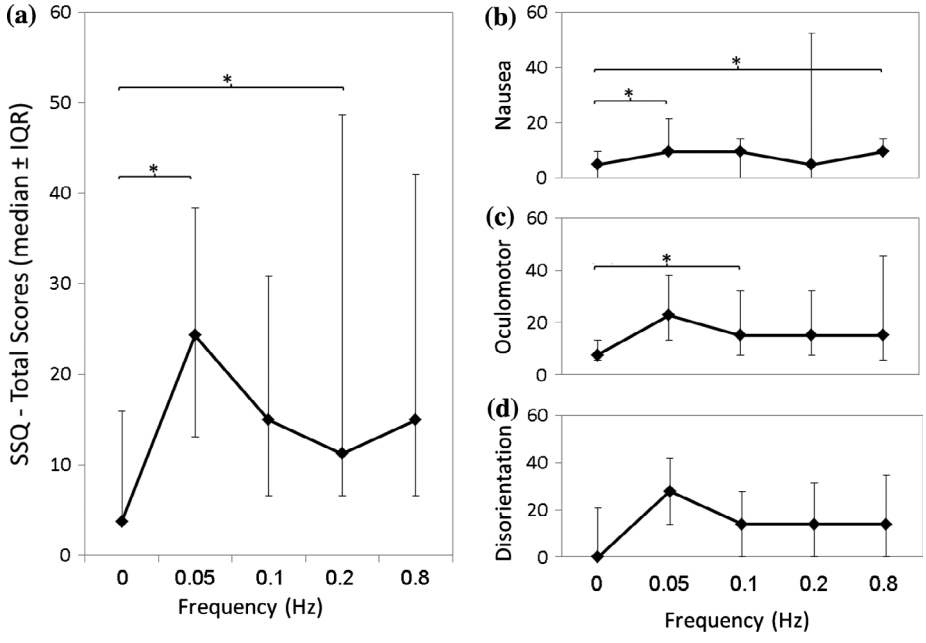

Figure 5. Frequency responses of the SSQ results (median with IQR) in Experiment 2: (a) Total SSQ scores; (b) nausea sub-scores; (c) oculomotor sub-scores; (d) disorientation sub-scores.
Notes: *Sig. different from other conditions, Wilcoxon signed-rank, $p < 0.05$.

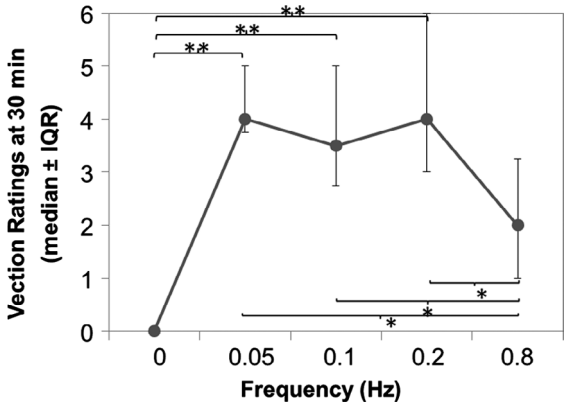

Figure 6. Frequency responses of vection ratings at the end of the 30-min exposure in Experiment 2. Median and IQR are shown.
Notes: *Sig. different from other conditions, Wilcoxon signed-rank, $p < 0.05$. **$p < 0.01$.

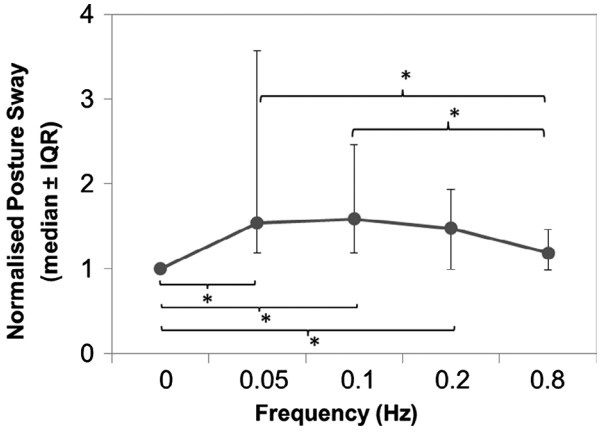

Figure 7. The frequency responses of the rms postural sway during the 30-min exposure for the 12 participants in Experiment 2.
Note: Wilcoxon signed-rank, $p < 0.05$.

While Type A contradicts previous studies, Type B does not. We discuss these two types of frequency response below.

6.1. Type A: frequency responses of VIMS with constant rms velocity

The frequency responses of VIMS have been investigated by Duh et al. (2004) and Diels and Howarth (2012) using VOs whose rms velocities were kept constant (see Table 1). Both studies presented findings that contradict the Type A response observed in this study. Duh and his colleagues used rotating VOs mixed with physical rotations in their study, so our findings differ from theirs possibly due to differences in the movement axis of VOs and/or the addition of vestibular motion cues. However, Diels and Howarth studied VOs along the fore-and-aft axis as we did and used a star-field VO pattern similar to ours, yet came to a different conclusion that VIMS peaked at 0.2 Hz. So what could have led to the discrepancy between our results and theirs?

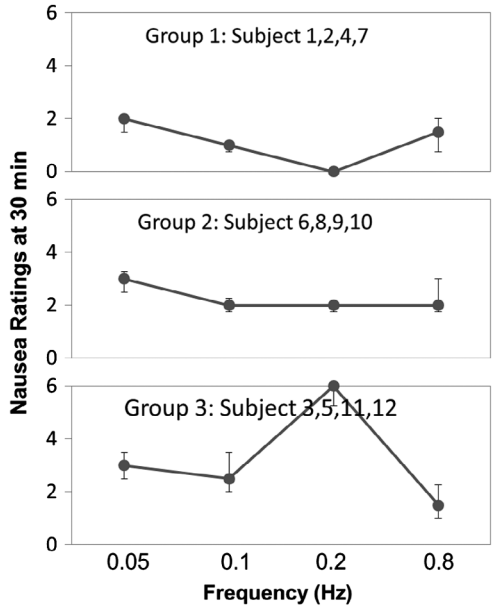

Figure 8. Grouping of the nausea ratings at the end of the 30-min exposure in Experiment 2. Participants in Groups 1, 2 and 3 had the lowest, medium and highest nausea ratings at 0.2 Hz, respectively.

Diels and Howarth studied the frequency responses of VIMS in two experiments. In their first experiment where the frequency ranged from 0.025 to 0.2 Hz, they found that VIMS increased with increasing frequency. In the second experiment involving a higher frequency range from 0.2 to 1.6 Hz, they found that VIMS reduced with increasing frequency. It is unfortunate that 0.2 Hz was at the upper end of the frequency range in their first experiment and at the lower end of the frequency range in their second experiment. As the two experiments used different subjects, the finding that levels of nausea peaked at 0.2 Hz might be confounded by individual variation. Our raw data support the speculation that subject variations may explain the difference between our findings and those of Diels and Howarth (2012). A large inter-subject variation was observed in the nausea data collected at 0.2 Hz (see Figure 3). Closer inspection showed that some participants reported lower levels of nausea at 0.2 Hz than at other frequencies (Figure 8: Group 1); some had similar levels of nausea regardless of frequency (Group 2); and some reported higher levels of nausea at 0.2 Hz (Group 3). When all three groups were added together, no statistically significant results were found. Hence, a slight skew in subject sampling might have caused a peak at 0.2 Hz. In this study, both Experiments 1 and 2 confirmed the flat frequency responses of VIMS when the VO rms velocities were kept constant. However, when the rms velocity of VOs was 22 m/s, we did find a significant increase in nausea ratings when the VO frequency was increased from 0.05 to 0.1 Hz. More studies are needed to confirm the flat VIMS frequency response when the rms velocity of VOs remains constant.

Despite the controversy, the Type A response is consistent with a hypothesis proposed by So, Ho, and Lo (2001). So and his colleagues hypothesised that for VOs with similar scene complexity and similar velocity, the same level of VIMS would be provoked, though they did not test it. After all, it would be reasonable to assume that the Type A response occurs only within a certain frequency range. At one extreme end of the frequency range (e.g. 0 Hz), VIMS levels would be greatly reduced as reported in Experiment 2. In this sense, if the frequency range is very large, the Type A response would ultimately be reduced to the Type B response.

6.2. Type B: frequency responses of VIMS with constant amplitude

In contrast to the Type A frequency response, the Type B frequency response predicts increased nausea with increasing VO frequency up to 0.2, 0.8 and 3.2 Hz depending on the amplitude of VOs. This suggests that when the amplitude of VOs is kept constant, levels of nausea will increase to a certain peak when the frequency of VO is increased. Nausea peaked at 0.2 Hz when VOs had a constant amplitude of 100 m (Figure 2). This peak increased to 0.8 and 3.2 Hz when the constant amplitude of VOs was reduced to 25 and 6.25 m, although 0.8 and 3.2 Hz hit the upper limits of the range of conditions investigated in our study.

As mentioned in the introduction and summarised in Table 1, there have been two VIMS studies in which the amplitude of VOs was kept constant – those of Lin and Donald (2005) and Yokota et al. (2005). Even though these two research groups studied VOs along different axes (roll oscillation or imposing roll oscillation on forward navigation) and the scene contents were different (virtual environments with complex objects), it is still (or even more) interesting to see how their observations compare with ours. In Lin and Donald (2005), the amplitude of the roll scene oscillations was maintained at 60°, and VIMS levels were found to increase significantly from 0.035 to 0.08 Hz, before reducing slightly (not statistically significant) to 0.213 Hz. On the other hand, in Yokota et al. (2005), the VOs along the roll axis had a constant amplitude of 30°, and they found that people with high motion sickness susceptibility had significantly stronger autonomic body responses at 0.1 Hz than at other frequencies. In a word, these two studies have both observed an increase-and-peak pattern in the frequency responses of VIMS, similar to the current Type B response, especially when the amplitude was kept at 100 m. Although the general patterns are similar, the frequency at which the frequency responses of VIMS peak varies from study to study. In our study, the peaks of VIMS appeared at different frequencies depending on the VO amplitude. Interestingly, an inverse proportional relationship between the peaking frequencies and the controlled amplitudes was observed. As we increased the controlled amplitudes from 6.25 to 25 m and further to 100 m, the reported VIMS levels peaked at the decreasing frequencies of 3.2, 0.8 and 0.2 Hz, respectively. This trend was also observed by Lin and Donald (2005) and Yokota et al. (2005). While Lin et al. found a peak at 0.08 Hz for a roll oscillation amplitude of 60°, Yokota et al. noted one at the higher frequency of 0.1 Hz for a lower roll oscillation amplitude of 30°. Therefore, in the case of a Type B frequency response of VIMS, the higher the amplitude of VOs, the lower the frequency at which a peak would occur.

Frequency selectivity in human vestibular systems (Griffin 1996) and human auditory systems (Meddis, O'Mard, and Lopez-Poveda 2001) are well reported. Hence, it should come as no surprise that humans also exhibit frequency selectivity in VIMS. Indeed, research has shown that rapid VOs will lead to reductions in VIMS (Ji, So, and Cheung 2009). The present results contribute towards a better understanding of the frequency characteristics associated with VIMS. In particular, the two types of frequency responses of VIMS found in this study suggest that, within the frequency range from 0.05 to 0.8 Hz, VIMS is more determined by the velocity of the VOs than by the amplitude or frequency of the VOs.

6.3. Comparing the frequency responses of nausea, vection and postural sway

In Experiment 2, nausea, vection and postural sway were measured simultaneously. Their responses changed as the frequency of the VOs that were used to provoke them increased from 0 to 0.8 Hz. Inspection of Figures 4–7 reveals that as the frequency of VOs increased from 0 Hz (stationary) to 0.05 Hz, all three responses grew significantly stronger ($p < 0.05$, Wilcoxon tests). However, as frequency increased from 0.05 to 0.8 Hz, levels of VIMS did not change, while both vection and postural sway weakened significantly ($p < 0.05$, Figures 6 and 7). Note that the velocity of VOs was kept constant in Experiment 2. Future studies are needed to investigate the frequency responses of vection and postural sway while keeping the amplitude of VOs constant.

7. Conclusion

The frequency responses of VIMS were flat when the velocity of VOs was held constant, while VIMS levels increased to a certain peak when the amplitude of VOs was kept still. These findings indicate a dominant role of velocity in VIMS severity. Moreover, since the control of velocity and amplitude clearly affects the frequency responses of VIMS, simply plotting VIMS levels against frequency without labelling the control variable may not be the best way to visualise the frequency plots. Last but not least, our results suggest that game designers can reduce VIMS for players through manipulating the velocity and amplitude of the visual motions. While this paper does provide useful references for game designers, future work testing more combinations of VO

amplitude and velocity would eventually lead to more complete guidelines for designing games that are less likely to provoke VIMS.

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