The Two-Frequency-Response Hypothesis on Vection: An Extended Study Using an Immersive VR Environment

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16 August 2018

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by

Wong, Tak Wa

This is to certify that I have examined the above PhD thesis
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Table of Contents

List of Tables

List of Figures

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Abstract

Viewers of Virtual Reality (VR) simulations often feel like they are moving even though they are actually stationary. This phenomenon is called vection or illusions of self-motion. The effects of oscillation frequency on vection along different axes have been studied with fixed velocity and fixed amplitude by Chen et al. (2016) and Fu (2017). Results suggest that in contrast to the literature, there were two different types of frequency response curves instead of one, depending on either velocity or amplitude held constant. This has been referred to as the “two-frequency-response (2FR)” hypothesis. This hypothesis can explain inconsistent frequency responses associated with vection in the literature, but it has only been tested with screen-based projected images. This study examines the 2FR hypothesis in an immersive VR environment. In Experiment 1, viewers were exposed to an immersive VR disco light environment presented on an HTC VIVE headset. Dotted disco lights were moving according to selected combinations of five levels of frequency, rms velocity, and amplitude. Results show that the 2FR hypothesis is applicable, but the shape of the response curve under constant amplitude was different from the findings of Fu (2017). One possible reason for the difference in results might be the differences in scene complexity. Experiment 1 used oscillating patterns in two dimensions while Fu used contrasted stripes of one dimension. As such, the vertical spatial complexity in this study was found to be significantly higher than that in Fu. In Experiment 2, the contrasted stripe patterns used in Fu were adopted and presented in the HTC VR environment. Results indicate that the findings of Experiment 1 still hold. This suggests that the addition or removal of vertical spatial complexity did not affect the frequency response of vection. Future work to identify the cause of different frequency response shapes is required. The current work demonstrates that the 2FR hypotheses holds for vection generated using a VR headset. Studying the frequency responses of vection with changing amplitude and velocity of scene movement should be avoided.

Chapter 1: Introduction

1.1 Vection

Vection (illusions of self-motion) refers to a phenomenon in which self-motion is perceived in the absence of physical movement. Vection can be induced visually. When a large part of the field-of-view moving, a viewer feels like he/she has moved even though the surroundings are stationary. For example, when people look at the sky and focus on a moving cloud, they can feel themselves and the ground moving instead of the cloud (Brandt, Dichgans & Koenig, 1973).

Vection can be generated by stimulating multiple sensory modalities such as the auditory (Väljamäe, 2008), the vestibular, (Lepecq, 2006) and the visual (Dichgans & Brandt, 1987). This dissertation focuses on vection induced by visual modality. When a large field-of-view is moving, viewers get the illusion that they are moving in the opposite direction. In an oscillating scene, a viewer may feel that they are oscillating in the opposite direction. One of the oscillations is sinusoidal oscillation. It has three factors which are velocity (v), frequency (f), and amplitude (A). The relationship of these factors can be described by following equation:

$$v = \sqrt{2}\pi f A.$$

The two-frequency response hypothesis (TFH) was proved by Chen et al. (2016) using an optokinetic drum with a projector. This hypothesis has not been studied using a head-mounted immersive stereo Virtual-Reality (VR) environment. A head-mounted VR is a popular technology of this age. Companies continue to develop and release new VR goggles. VR technology can be applied to gaming, movies, and training programs (such as pilot training). Investigation on vection can improve the experience and effectiveness of VR (Riecke, 2010).

1.2 Scene Complexity

The complexity of a scene can be represented by its spatial frequency. The effect of spatial frequency on vection has been studied by Hu et al. (1997). Another factor that can affect the vection magnitude is edge rate acceleration. The effect of edge rate acceleration on vection has been studied by Lo & So, (2001) as functions of both scene velocity and scene complexity.

1.3 Objectives and Hypotheses

This study aims to test the two-frequency responses (2FR) hypothesis on vection in a head-mounted immersive stereo VR environment with 3D virtual object. The frequency responses of vection as functions of constant amplitude VR scene oscillations and constant velocity VR scene oscillations will be examined in this dissertation. Besides the 2FR hypothesis, the scene complexity has also been studied due to the changing visual stimuli.

The major hypotheses of this dissertation are:

H1: Changing the visual stimuli from optokinetic drum to head-mounted VR environment will not affect the vection magnitude.

H2: The two-frequency response (2FR) hypothesis holds when head-mounted immersive stereo VR environment is used as visual stimulus.

H3: Changing of scene complexity would affect vection magnitude.

Chapter 2: Literature Review

2.1 Vection and Sensory

Vection (illusions of self-motion) refers to a phenomenon in which self-motion is perceived in the absence of physical movement. Information about movement and spatial orientation of the body can be provide by different sensory modalities. Studies suggests that is a division of labor (Howard, 1986; Warren, 1995). Some studies proved that vestibular system is more sensitive for high-frequency range oscillations(>1Hz) (Diener HC et al., 1982; Diener HC et al., 1984; Grossman GE et al., 1989; Melville-Jones G, Young LR, 1978) and visual system is more sensitive for low-frequency range oscillations(<1Hz) (Bardy et al., 1996; Lestienne, F. et al., 1977; van Asten et al., 1988; Yoneda, S., & Tokumasu, K., 1986).

Information conflict between different sensory systems can elicit sickness. For example, passengers can feel the movement of a car by vestibular system, but they feel they are stationary by visual system if they do not see the outside of car. The conflict between systems can elicit sickness. The cross-frequency (0.06Hz) was proposed by (Duh HB, Parker DE, Philips JO, Furness TA, 2004). Both vestibular and visual were sensitive in this frequency, so sickness would be more likely to be elicited in this frequency.

2.2 Scene complexity

Scene complexity can be measure by spatial frequency which is defined as cycles of changes in luminance per unit visual angle, or cycles per degree (Brandt, 1973; Dichgans & Brandt, 1978; Henn, V. et al., 1980; Hu et al., 1989; Hu et al., 1997; Koch, K. L. M. et al., 1990; Muller, C. H. et al., 1990). Scene complexity is an effective factor of vection. Besides scene complexity, movement of scene is another effective factor of vection. Considering the scene complexity and scene movement, spatial velocity has been proposed by Lo (2001). Spatial velocity (SV) was developed as a metric for quantifying visual scene movement. The SV metric consists of two components: spatial frequency and the r.m.s. navigation velocities of the viewers. Therefore, SV can be increased by changing the spatial frequency with constant navigation velocities. Lo (2001) analyzed the relationship between SV and cybersickness and found that the level of cybersickness was increased with SV.

2.3 Two-Frequency Response Hypothesis

The two-frequency response hypothesis (TFH) was proposed and proved by Chen (2014). The study proposed that the frequency responses of perceived vection were different if the stimuli's frequencies were manipulated by changing the amplitude of the oscillations or changing the velocity of the oscillations. TFH has been studied with respect to different axes by Fu (2017). The hypothesis has been proved with respect to the yaw axis. Some researchers are studying vection in head-mounted VR environments (Juno Kim, & Michael, 2016; Riecke & Jordan, 2015; Berthoz, Lacour, Soechting, Vidal, 1979). TFH has not been studied in head-mounted VR environment. Studying the effects of frequency, velocity, and amplitude on vection is important for identifying the factor that can be an appropriate predictor for the perceived vection magnitude.

2.4 Factors Affecting Levels of Visually Induced Vection

The velocity of optical flow is one of the important factors. Hu et al. (1989) studied four levels of constant rotation speed (15, 30, 60, and 90 deg./s). The results show that vection magnitude increased as the optokinetic drum's rotation speed increased. When the rotation speed was between 15 to 60 deg./s, the vection dropped as rotation speed increased Another approach is keeping the optical flow static and increasing the edge rate acceleration (ERA). In Hettinger, Owen, & Warren (1985)'s research, the flowing velocity was kept constant but the ERA was increased (reducing the size of the flow pattern to increase the number of edges per unit distance). Results show that the perception of vection increased as ERA increased, reached a peak value and then decreased as ERA increased. In contrast to Hettinger, Owen, & Warren (1985), Hu et al. (1989) changed the flow velocity to increase ERA. These two researches obtained similar results. According to these results, ERA was found to be a main factor affecting the perception of vection.

Another significant factor is spatial frequency which is related to ERA. In Hu et al.'s (1997) research, the interior of the optokinetic drum (360 degrees) was evenly covered with 6, 12, 24, 48, and 96 pairs of black-and-white stripes. Results show that the yaw vection magnitude peaked when the drum was covered with 24 pairs. Fu's (2017) visual stimuli used 24 pairs in the yaw vection experiment.

Some previous studies found that a smaller field of view (FoV) reduces perceived vection (Allison et al., 1999; Dichgans & Brandt, 1978; Flanagan et al., 2002). However, the perceived vection was not affected by different display types such as three-dimensional (3D) TV, a projection screen, and a head-mounted display.

2.5 Summary of Literature Review

As concluded by previous research, the type of display does not affect the perceived vection. TFH should have been valid when the visual stimuli were changed from projector to head-mounted display. However, the size of the FoV changed the visual stimuli's display. Multiple factors changed when the visual stimuli were changed. The effect of changing the display was unclear.

In case of the spatial frequency, 24 periods in 360 degrees should be chosen to maximize the perceived vection. The previous related research (Fu, 2017) also used 24 pairs of black-and-white stripes in 360 degrees as visual stimuli.

Chapter 3: Experimental Setups and Measurements

3.1 Apparatus

A head-mounted VR device was used in both the experiments in this dissertation. The device model used was HTC VIVE. The resolution of the display was 2160 x 1600 for both eyes (1080 x 1600 per eye). Subjects could see the display screen through the round lenses. The angle of FoV was 80 degrees for each eye. The stimulus was played at 90 Hz refresh rate.

Figure 3.1 Photo of HTC VIVE goggle

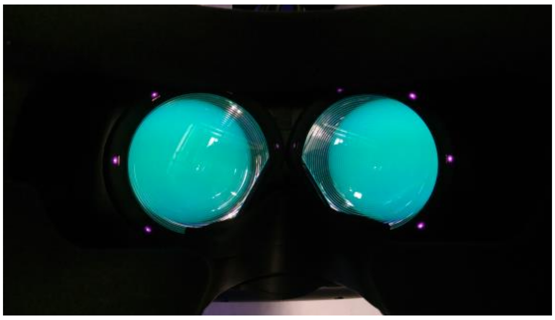


Figure 3.3 Display of VR goggles

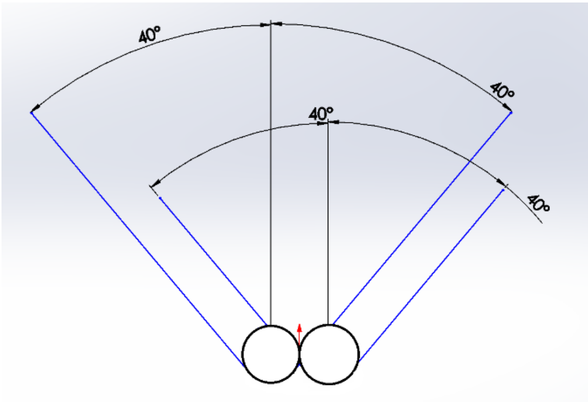


Figure 3.2 Field-of-View for each eye

The chin-rest kept the subjects' head stationary. Before the experiment, the chair was adjusted to a suitable height so that subject can rest their head comfortably on the chin-rest. Figure 3.4 is a photo that a subject was taking experiment. Figure 3.5 is a photo of virtual environment was used as visual stimuli in Experiments 1 and 2. Subjects were sitting in the center of the ring and below the ball. The ball is the light source that projecting the square dot pattern.

Figure 3.4 Subject was taking experiment

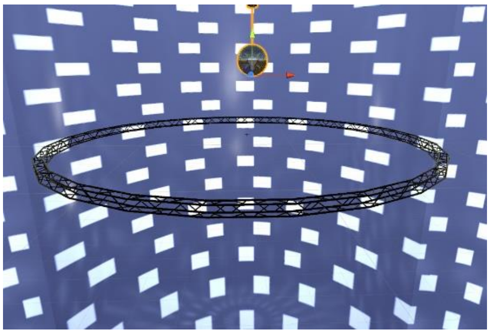


Figure 3.5 Virtual environment of visual stimuli

Table 3.1 Detail of apparatus

Apparatus	Specifications
Stimuli generating computer	Intel® core i7-6700K 4.00GHz CPU
	32GB RAM
	NVidia GeForce GTX-1080 graphics card
	Windows 10 Operation system
	Unity Game Engine
Stimuli Display	HTC VIVE

3.2 Vection Generating Stimuli

3.2.1 Vection generating stimuli in experiment 1

In Experiment 1, the visual stimulus was composed of the square dot disco light. The pattern of the light was projected on the wall inside the virtual environment. The light source was located above the subjects' heads. The light source was rotated along the yaw axis. This kind of visual pattern is typically used to induce vection along the yaw axis. The pattern has 24 repetitions in 360 degrees.

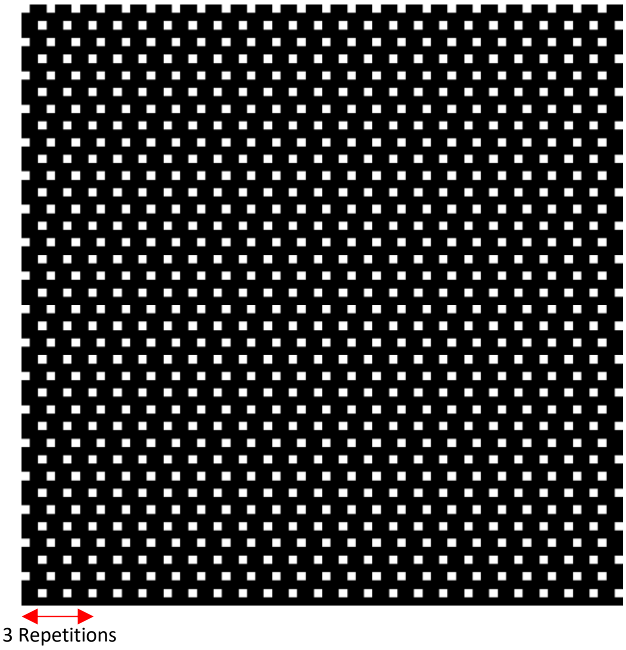


Figure 3.6 Pattern of light source for 360 degrees in Experiment 1

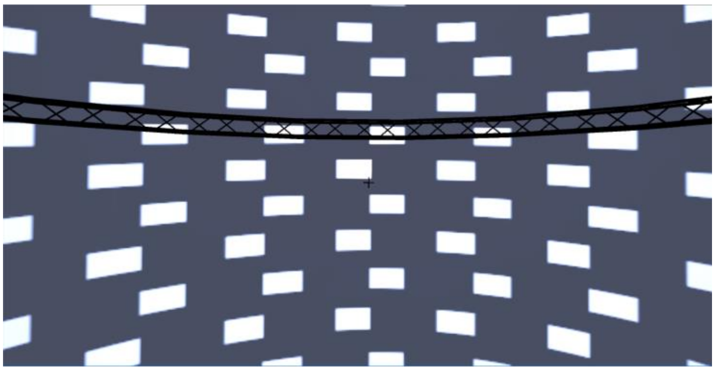


Figure 3.7 Scene inside virtual environment in Experiment 1

3.2.2 Spatial Frequency of stimuli in experiment 1

In Experiment 1, spatial frequency of stimuli was measured by combined method (Lo, 2001). The average horizontal spatial frequency is 0.0665 cycle per degree(cpd) and average vertical spatial frequency is 0.1355 cpd. The average radial spatial frequency is 0.1510 cpd.

3.2.3 Vection generating stimuli in experiment 2

In Experiment 2, the visual stimulus was composed of striped disco light. The pattern of light was projected on the wall inside the virtual environment. The light source was located above subjects' heads. The light source was rotated along yaw axis. This kind of visual pattern is typically used to induce vection along the yaw axis. The pattern has 24 repetitions in 360 degrees.

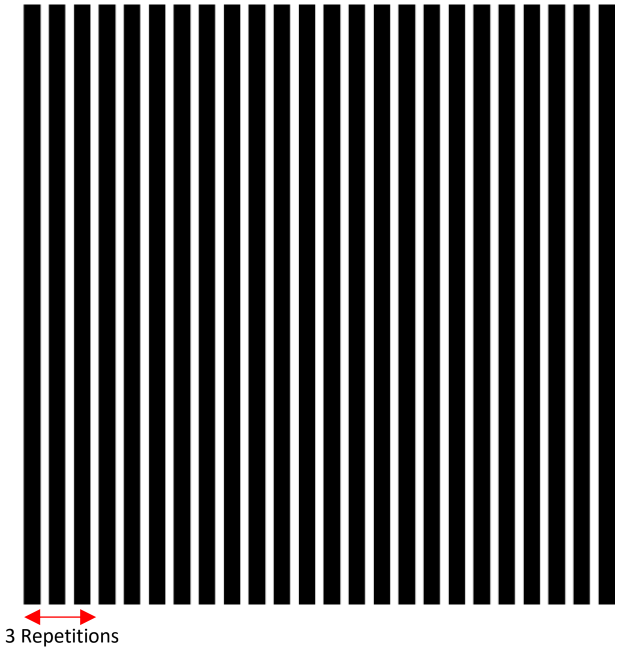


Figure 3.8 Pattern of light source for 360 degrees in Experiment 2

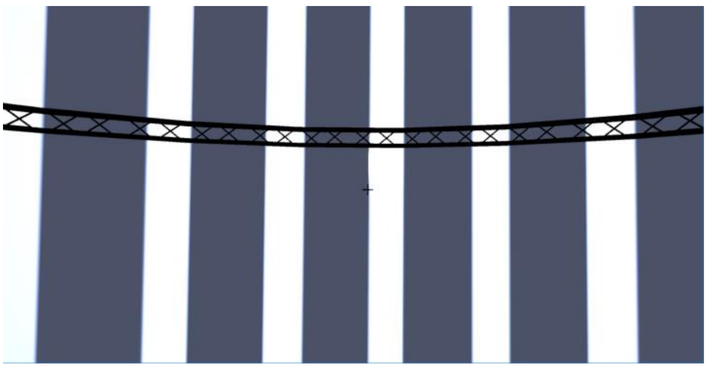


Figure 3.9 Pattern of light source for 360 degrees in Experiment 2

In both the stimuli in experiments 1 and 2, a black cross was drawn at the center of the scene. During the experiments, subjects were instructed to keep their eyes fixed on the cross.

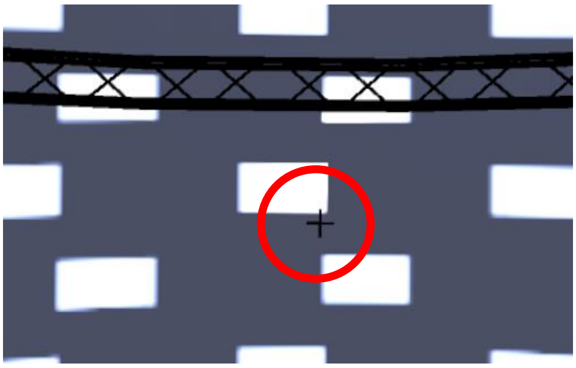


Figure 3.10 Eyes fixation point in Experiment 1

3.2.4 Spatial Frequency of stimuli in experiment 2

In Experiment 2, spatial frequency of stimuli was measured by combined method (Lo, 2001). The average horizontal spatial frequency is 0.0509 cycle per degree(cpd) and average vertical spatial frequency is 0.0976 cpd. The average radial spatial frequency is 0.1100 cpd.

3.3 Measurements

3.3.1 Visual acuity

All subjects participating in the experiments were required to have normal or correct-to-normal visual acuity. Before the subjects could participate in the experiments, they needed to pass the visual acuity test. Subjects needed to wear glasses if they had glasses. Participants needed to pass both near and far visual acuity tests for each eye separately and both eyes together. The viewing distance between the targets and subjects' eyes was 14 inches for near point visual test and 20 feet for far point visual test. Optec2000 Vision Tester (Stereo Optical Corp.) was used for the test.

In the visual acuity test, there were 14 targets corresponding to visual acuity from 20/200 to 20/13. Each target consisted of three broken rings and one complete ring. Subjects needed to point out the position of the complete ring (top, bottom, left, or right). Normal vision is known as 20/20 vision. Subjects were required to at least point out answers of the 1^{st} to 10^{th} targets correctly. The instructions and the test chart are shown in Appendix 3.1.

Figure 3.11 Optec 2000 Vision Tester (Stereo Optical Corp.)

3.3.2 Motion sickness susceptibility questionnaire short-form (MSSQ-short)

Subjects were required to fill a MSSQ-short to find out how susceptible to motion sickness they are (Golding, 1998). Subjects needed to rate how often they feel sick or nauseated during using facilities listed in table 3.2. The same questions needed to be answered twice for experience as a child (before age 12) and experience over the last 10 years. Based on the answers, MSSQ raw scores and percentage scores were computed to indicate subjects' susceptibility to motion sickness. MSSQ-short and the scoring method are shown in Appendix 3.2.

Table 3.2 facilities list in MSSQ-short

Car
Buses or Coaches
Trains
Aircraft
Small Boats
Ship, e.g. Channel Ferries
Swings in playgrounds
Roundabouts in playgrounds
Big Dippers, Funfair Rides

3.3.3 Simulator sickness questionnaires (SSQ)

Participants were required to fill an SSQ before and after the exposure to visual motion to evaluate whether they felt sick. Questionnaires consisted of 27 symptoms which are commonly experienced by users of virtual reality systems. Each item was rated with the scale of none, slight, moderate, and severe. The following table lists all the 27 symptoms.

Table 3.3 SSQ symptom list

1. General discomfort	10. Nausea	19. Aware of breathing
2. Fatigue	11. Difficulty concentrating	20. Stomach awareness
3. Boredom	12. Mental depression	21. Loss of appetite
4. Drowsiness	13. "Fullness of the head"	22. Increased appetite
5. Headache	14. Blurred vision	23. Desire to move bowels
6. Eyestrain	15. Dizziness eyes open Dizziness eyes close	24. Confusion
7. Difficulty focusing	16. Vertigo	25. Burping
8. Salivation increase Salivation decrease	17. Visual flashbacks	26. Vomiting
9. Sweating	18. Faintness	27. Other

The total scores and the three sub-scores (nausea score, oculomotor score, and disorientation score) were calculated to rate the level of sickness (Kennedy, Lane, Berbaum, & Lilienthal, 1993). Table 3.3 show the weightings of three sub-scores. The weighting of total score is the sum of the three sub-scores. The SSQ is attached in Appendix 3.3 and the scoring method is attached in Appendix 3.4. If the participants reported a total score larger than 7.48 before exposure to visual motion, they were required to take a 10-minute rest and then fill the SSQ again. If the total score was still higher than 7.48, they were asked to do the experiment on another day (Stanney, Kingdon, Graeber, & Kennedy, 2002).

Table 3.4 Weightings of selected symptom to SSQ sub-scores: Nausea (N), Oculomotor (O), Disorientation (D)

Weights for Symptoms			
Symptoms	Nausea	Oculomotor	Disorientation
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eye strain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		

3.3.4 Computer game experience

In experiments 1 and 2, electronic games experiment of subject was record. Subjects need to report number of hours (0hrs, 5hrs, 10hrs, 15hrs, >20hrs) they spend on electronic games per week.

3.3.5 Vection

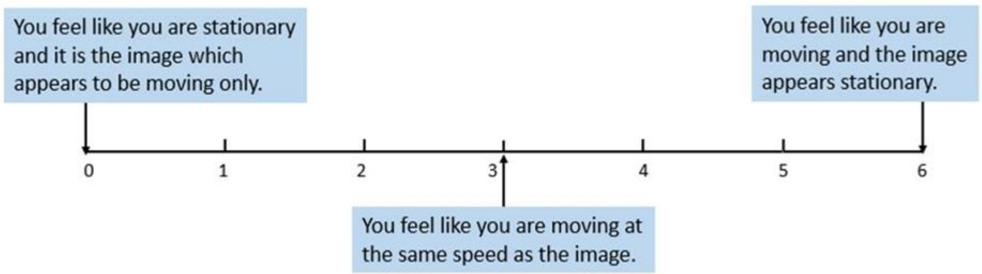


Figure 3.12 Description of vection magnitudes for each point in instruction

In experiments 1 and 2, the vection magnitude was subjectively measured to ascertain the level of intensity with which subjects experienced self-motion illusions. Seven-point Likert scale ranging (Webb & Griffin, 2003) was used to rate the vection magnitude. This scale was also adopted in Chen (2014) and Fu (2016).

The range of the 7-point scale is from 0 to 6. Point 0 implies that "*subject perceives that the only thing moving is the visual stimulus and subject remains stationary (No Vection)*". Point 3 implies that "*subject perceives that he/she is moving at same speed as the visual stimulus*". Point 6 implies that "*subject has a strong feeling that he/she is moving, and the visual stimulus is stationary (Total Vection)*" (quoted from Webb & Griffin, 2003).

Table 3.5 Scale of vection rating

Vection Rating Scale	
0	Subjects feel like they are stationary and visual stimulus is the only thing moving
3	Subjects feel like they are moving at the same speed as the visual stimulus
6	Subjects feel like they are moving, and the visual stimulus is stationary.

Chapter 4: Frequency responses of vection when viewing square-patterns oscillating along yaw axis: Keeping rms velocity constant VS Keeping amplitude constant

This chapter describes Experiment 1 that studied the effect of changing the optokinetic drum to a head-mounted stereo VR environment on frequency responses of vection. The rms velocity, amplitude, and frequency consists of five levels (rms velocity: 8, 16, 32, 64, 128 deg./s; amplitude: 18, 36, 72, 144, and 288 degrees; frequency: 0.025, 0.05, 0.1, 0.2, 0.4 Hz;). The experiment consisted of four repeated sessions with at least 12-hour intervals adopting a within-subject design. Sixteen subjects (10 males, 6 females) participated in the experiment. The light consisted of white square dots. The disco light alternatively oscillated sinusoidally. Results supported TFH as proposed by Chen (2014) and were different from Fu (2017). When the rms velocity was fixed at 32 deg./s or lower, the yaw vection dropped as amplitude decreased (or frequency increased). When the rms velocity was fixed at 64 deg./s, the yaw vection was constant regardless of amplitude increase or decrease. When the rms velocity was fixed at 64 and 128 deg./s, the yaw vection increased as amplitude increased. Analyses of the effects of velocity indicated that the lower the velocity, the lower the vection magnitude.

4.1 Research Gaps and Objectives

As reported earlier, TFH has been studied in some axes with optokinetic drum but not in a head-mounted immersive stereo VR environment. Experiment 1 is aimed to fulfil a research gap. In this experiment, the effect of changing the optokinetic drum to a head-mounted stereo VR environment on frequency responses of vection was studied. It is hypothesized TFH holds, and frequency responses were similar to the previous study which used optokinetic drum as visual stimulus (Fu 2017).

4.2 Methods

4.2.1 Participants

Sixteen subjects (6 females and 10 males) aged between 20 to 30 years (average of 23 years old) participated in the experiment and completed all repeated sessions in Experiment 1. All participants passed the line length estimation test with R-square greater than 0.9 before the start of the experiment. All the participants had normal or correct-to-normal visual acuity. They all signed a consent form voluntarily before the start of the experiment. All participants filled the MSSQ-short to find out how susceptible they were to motion sickness (Golding, 1998; Golding, 2006). An average percentile score of 46.99% indicated that the sample was slightly insusceptible. The computer game experience of subjects

4.2.2 Apparatus and stimulus

Experiment 1 used disco light with square dots as the stimulus. The participants wore HTC VIVE goggles to be exposed to the virtual room with disco light.

4.2.3 Experimental design

Experiment 1 had three independent variables: (i) amplitude of visual motion oscillations; (ii) velocity of visual motion oscillation; and (iii) repetition. Due to the three-way relationship of amplitude, velocity, and frequency ($v = \sqrt{2}\,\pi\, fA$), combinations of velocity and amplitude form a many-to-one relationship with the frequency of the visual oscillations. In this experiment, amplitude, rms velocity, and frequency consisted of five levels. Low frequencies were chosen since visual system is more sensitive for low-frequency range oscillations. 0.025, 0.05, 0.1, 0.2, 0.4 Hz were chosen in this experiment. 8, 16, 32, 64, and 128 deg./s were chosen since human have difficulty for distinguishing velocities beyond this range. For the Table 4.1 presents all the 37 conditions of the different combinations of amplitude, velocity and frequency.

Table 4.1 List of conditions in Experiment 1

Con #	freq (Hz)	rms v (deg./s)	amp (deg.)	Con #	freq (Hz)	rms v (deg./s)	amp (deg.)	Con #	freq (Hz)	rms v (deg./s)	amp (deg.)
1	0.4	8	4.5	14	0.2	32	36	27	0.4	256	144
2	0.2	8	9	15	0.4	64	36	28	0.00625	8	288
3	0.4	16	9	16	0.8	128	36	29	0.0125	16	288
4	0.025	2	18	17	0.025	8	72	30	0.025	32	288
5	0.05	4	18	18	0.05	16	72	31	0.05	64	288
6	0.1	8	18	19	0.1	32	72	32	0.1	128	288
7	0.2	16	18	20	0.2	64	72	33	0.2	256	288
8	0.4	32	18	21	0.4	128	72	34	0.4	512	288
9	0.8	64	18	22	0.0125	8	144	35	0.025	64	576
10	1.6	128	18	23	0.025	16	144	36	0.05	128	576
11	0.025	4	36	24	0.05	32	144	37	0.025	128	1152
12	0.05	8	36	25	0.1	64	144				
13	0.1	16	36	26	0.2	128	144				

In this experiment, the perceived vection magnitude and perceived speed were assumed as dependent variables. Vection magnitude was measured by a 7-point Likert scale ranging from 0 to 6. Perceived speed was measured by the ratio-scale method with reference condition – Con #19. Reference condition was the middle of the amplitude range (72 deg.), the middle of the rms velocity range (32 deg./s), and the middle of the frequency range (0.1 Hz). The average speed of the reference condition was assigned as 1, and there were nine choices of ratios provided: 1/16, 1/8, 1/4, 1/2, 1, 2, 4, 8, and 16.

4.2.4 Experiment procedures

All participants needed to pass the visual acuity test and line length estimation test and then training sessions were conducted. In the training session, participants were instructed about their task and exposed to three training conditions for pilot sessions.

There were 4 repeated sessions for each participant. In each session, participants filled the pre-exposure Simulator Sickness Questionnaire (SSQ) before the session was started. If the pre-SSQ total score was larger than 7.48, the session was scheduled to another date (Stanney et al., 2002). When the session started, participants were exposed to all 37 conditions in random order. The 37 conditions were divided into four groups. The first group consisted of ten conditions and another three groups consisted of nine conditions. In each group, participants completed the 9 or 10 conditions successively. Between each group, there was a 10-minute rest at least until no symptoms were ‘Moderate’ in SSQ. At the end, participants filled the post-exposure Simulator Sickness Questionnaire (SSQ).

For each condition, the disco lights would be turned off for 5 seconds. Then, participants would be exposed to a reference oscillation for 20 seconds. Next, the disco lights would be turned off again for 5 seconds. Last, participants would be exposed to signal oscillations and they reported perceived speed and vection orally. After the participants had reported the perceived speed and vection, the next condition would start.

4.3 Results

4.3.1 Learning effects

Table 4.2 shows the descriptive statistics for vection magnitude in the four repetitions. The mean of the vection magnitudes decreased in the first three repetitions and increased in the fourth repetition. Therefore, learning effects were tested first.

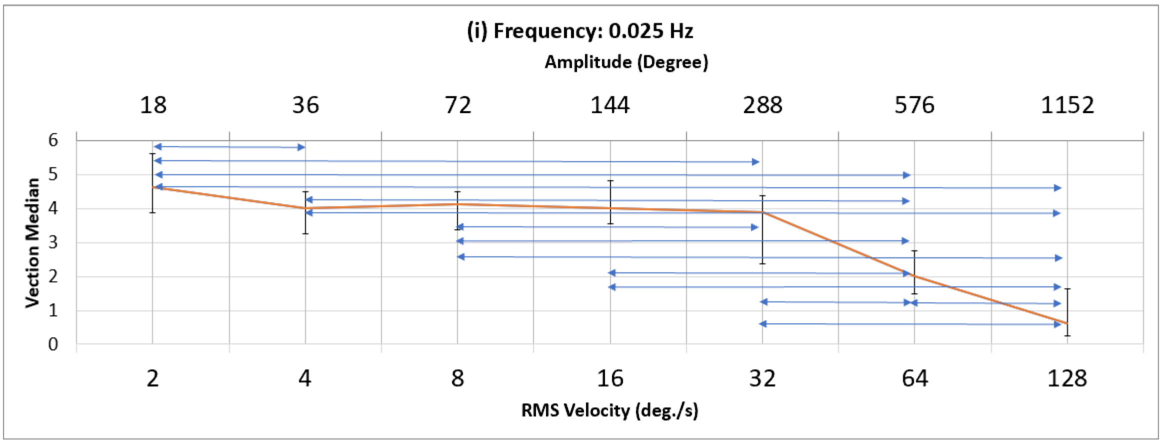
Table 4.2 Statistics for vection magnitude in 4 repetitions of Experiment 1

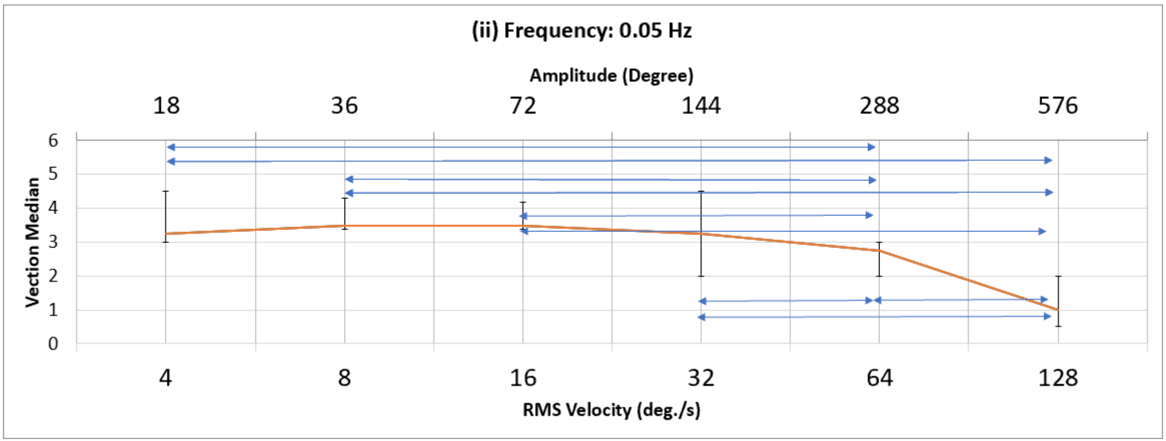
Repetition	Mean	Standard deviation	Minimum	25th percentile	Median	75th percentile	Maximum
1	3.018	1.760	0	2	3	4.5	6
2	2.938	1.775	0	1.5	3	4.5	6
3	2.791	1.688	0	1	3	4	6
4	2.829	1.681	0	1.5	3	4	6

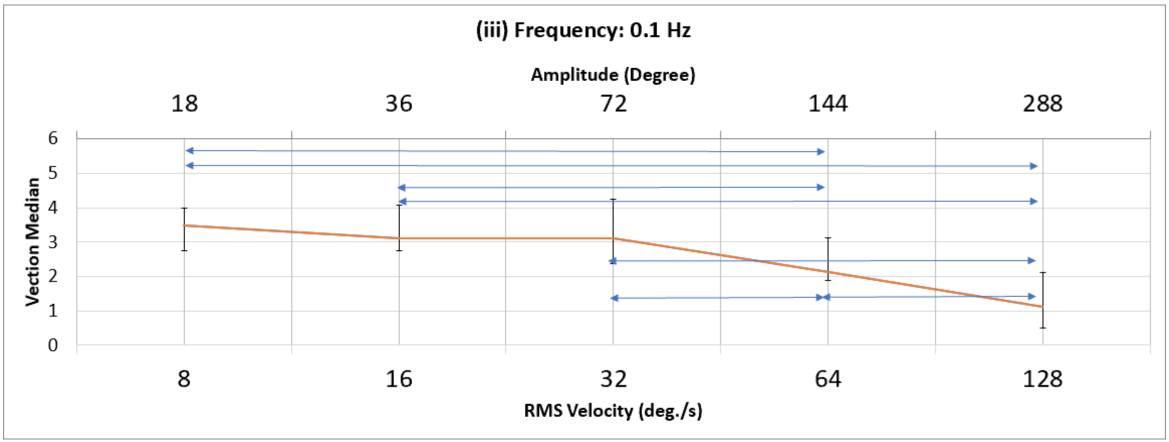
The perceived vection magnitudes were not normally distributed ($p<0.001$, Shapiro-Wilk). Thus, non-parametric tests were adopted here. Results showed that repetitions had a significant influence on vection for four repetitions ($p=0$, Friedman). When the data from Repetition 1 were excluded, the effects of the repetition still existed ($p=0.001$, Friedman). When the data from Repetition 1 and 2 were excluded, there were no learning effects ($p=0.362$, Friedman). Therefore, subjects' performance was supposed to be stable in repetition 3 and 4. And the subsequent analysis was based on the average ratings of repetition 3 and 4 for each participant with respect to each condition.

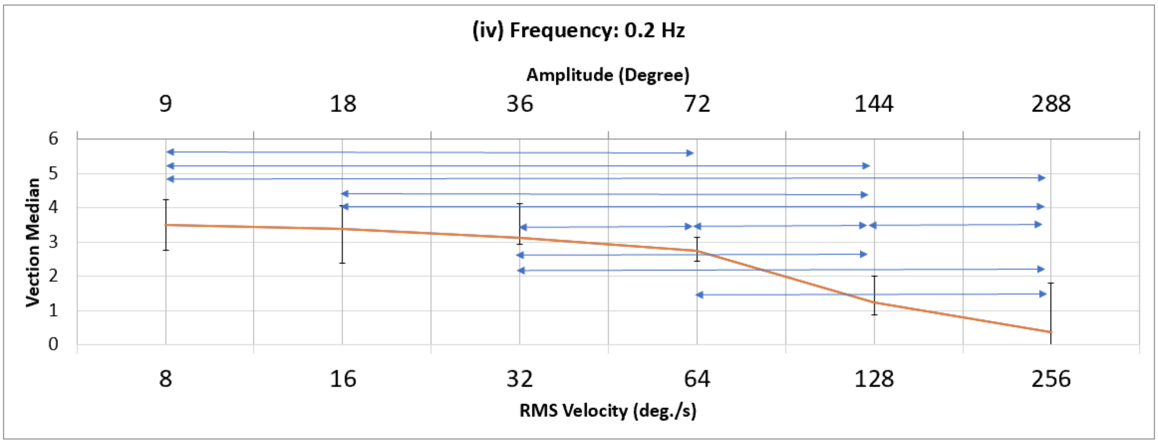
4.3.2 Vection magnitude under constant frequency

Under constant oscillation frequency, the following shows the medians of the vection magnitude ratings for five levels of frequency: (i) 0.025 Hz, (ii) 0.05 Hz, (iii) 0.1 Hz, (iv) 0.2 Hz, (v) 0.4 Hz. In the figures, the upper horizontal axes represent amplitude (degree) and the lower horizontal axes represent rms velocity (degree per second). Amplitude and rms velocity were proportional to each other in the same frequency. The horizontal double-sided arrows indicate significant differences in the two conditions ($p<0.05$, Wilcoxon). Results show that the vection magnitude decreased significantly as rms velocity (or amplitude) increased.









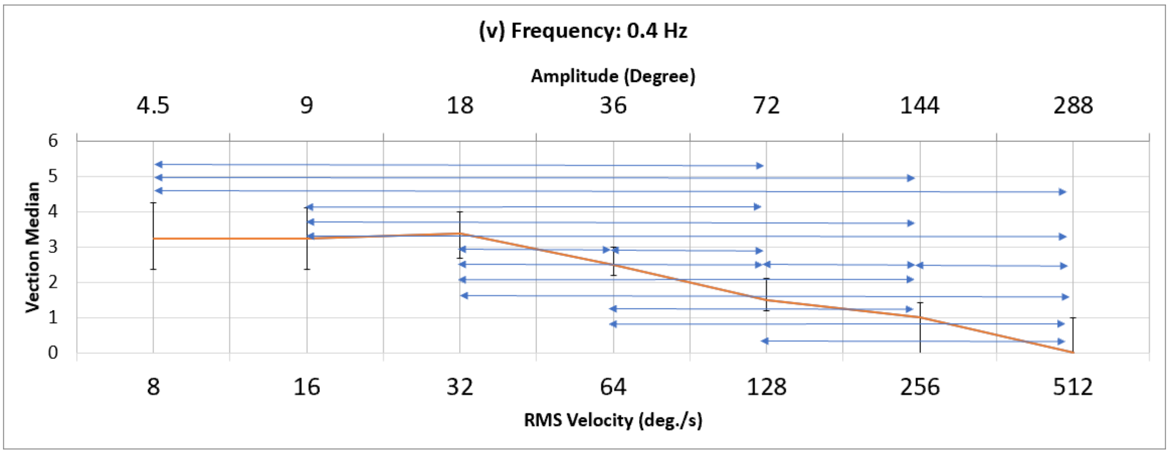
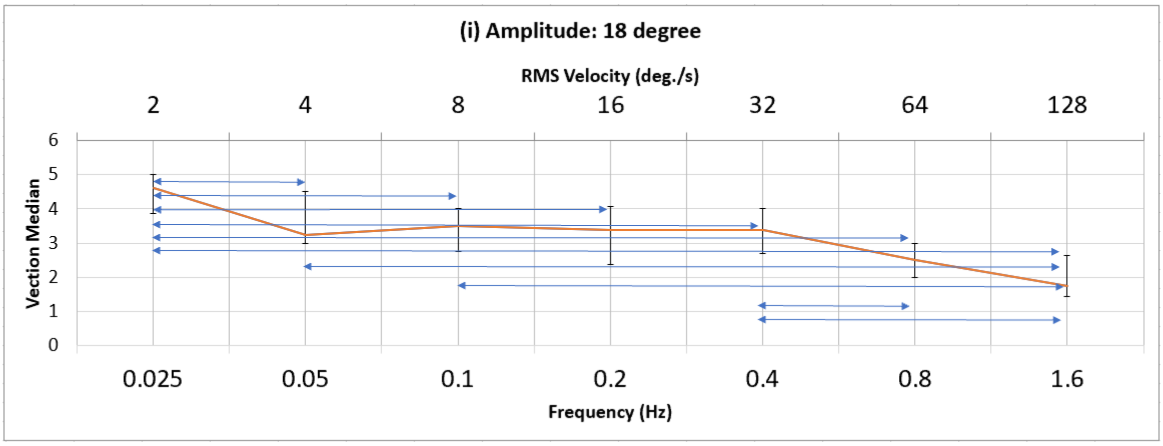
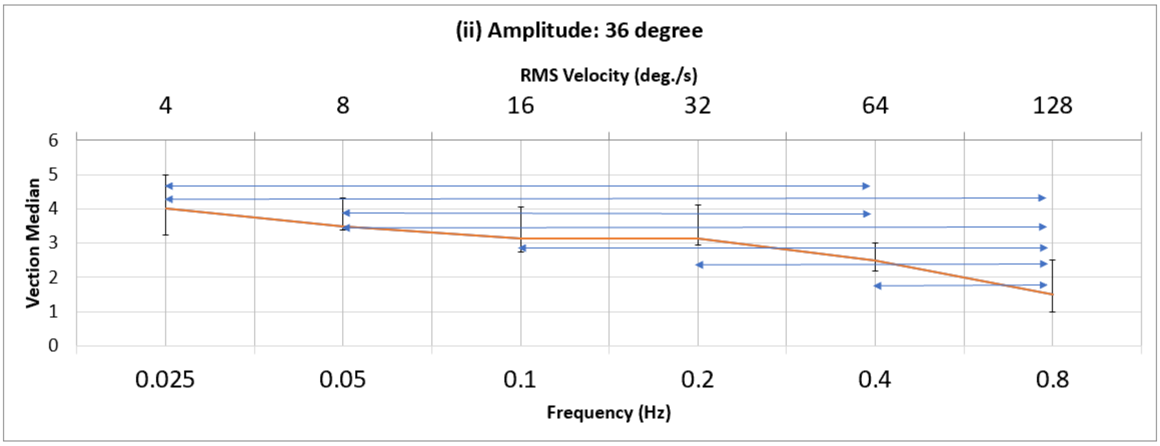


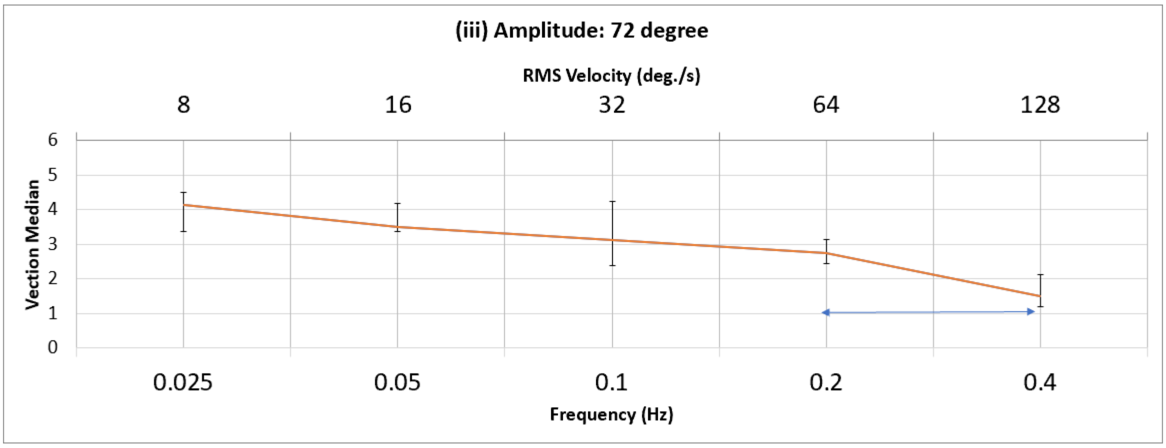
Figure 4.1 Medians of vection magnitude under constant frequency in Experiment 1 for five levels of frequencies: (i). 0.025 Hz; (ii). 0.05 Hz; (iii). 0.1 Hz; (iv). 0.2 Hz; (v). 0.4 Hz.

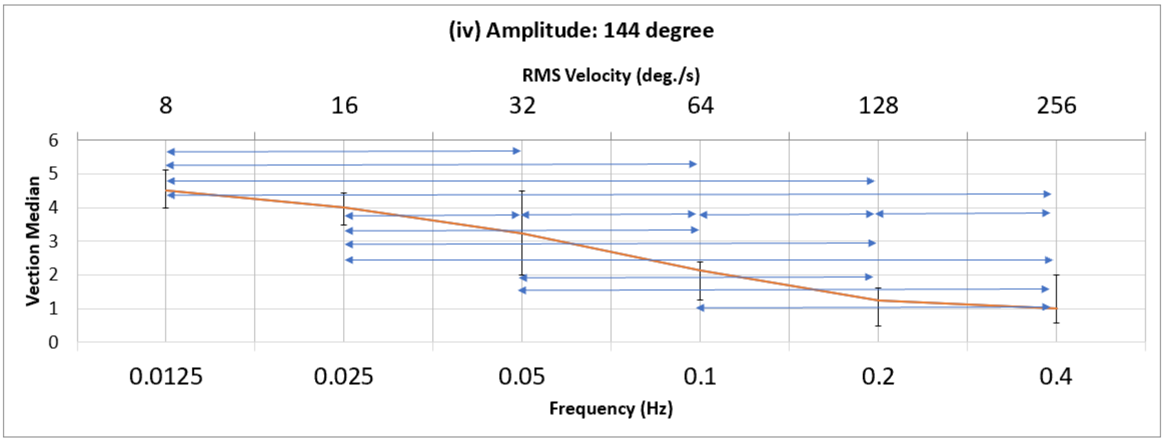
4.3.3 Vection magnitude under constant amplitude

Under constant oscillation amplitude, the following shows the medians of the vection magnitude ratings for five levels of amplitudes: (i) 18 degrees, (ii) 36 degrees, (iii) 72 degrees, (iv) 144 degrees, (v) 288 degrees. In the figures, the upper horizontal axes represent rms velocity (deg./s) and the lower horizontal axes represent frequency (Hz). rms velocity and frequency were proportional to each other in the same amplitude. The horizontal double-sided arrows indicate significant differences in two conditions ($p<0.05$, Wilcoxon). Results show that the vection magnitude decrease significantly as frequency (or rms velocity) becomes larger.









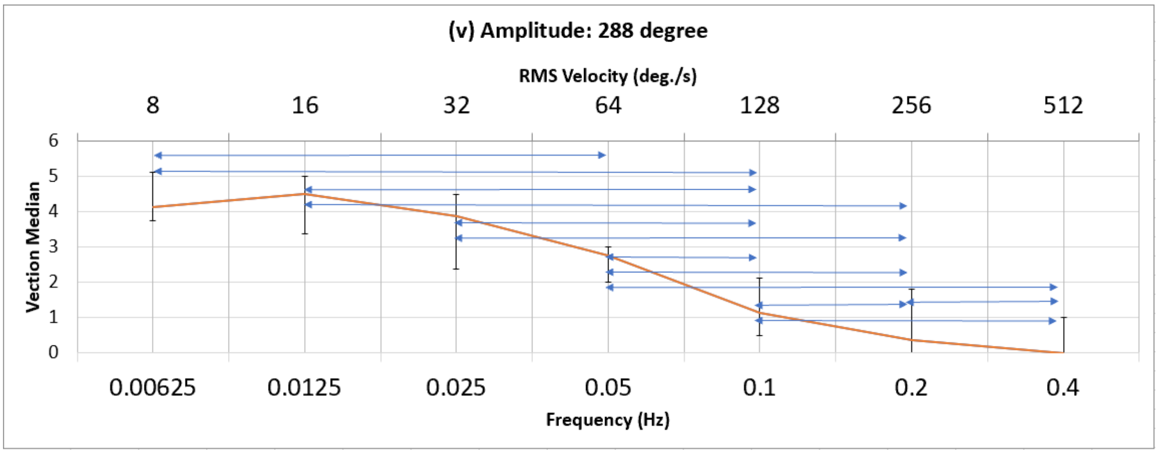
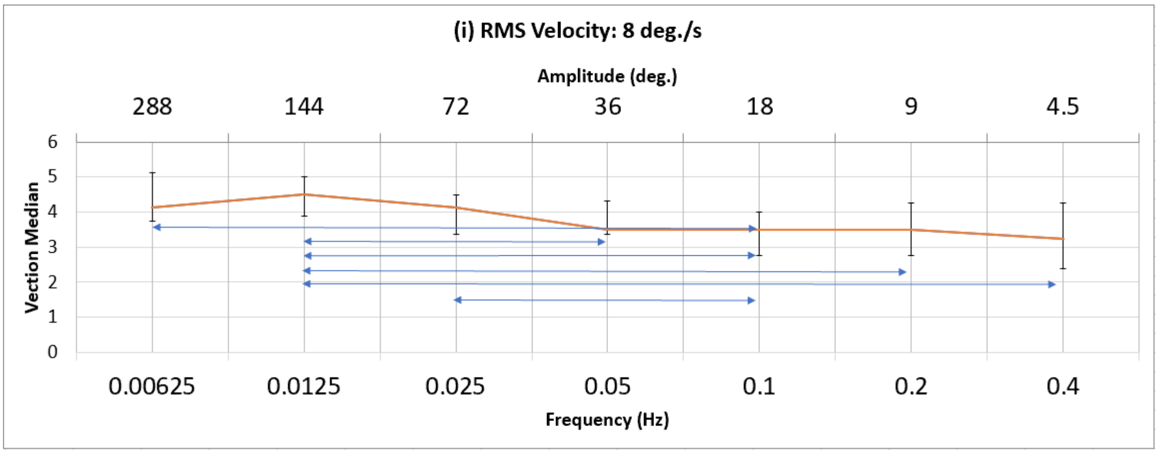
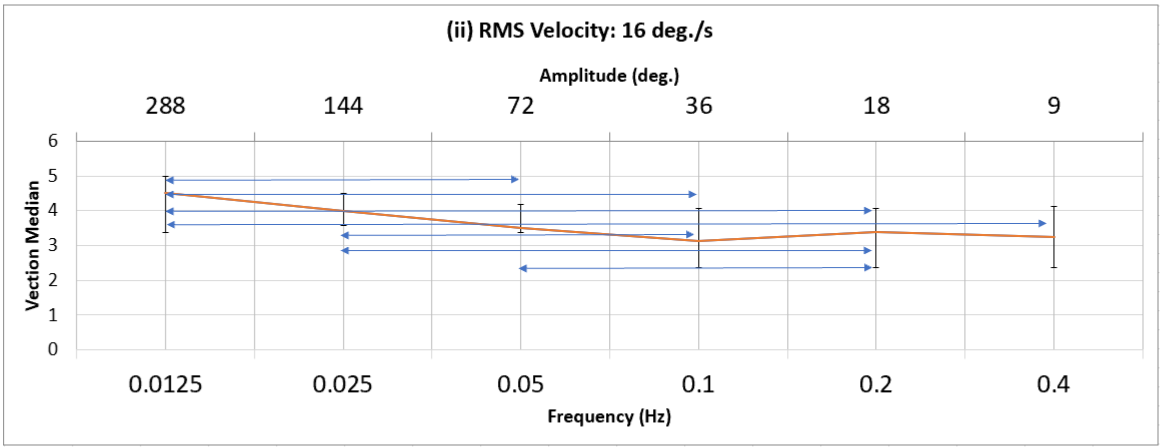


Figure 4.2 Medians of vection magnitude ratings under constant amplitude in Experiment 1 for five levels of amplitudes: (i). 18 degrees; (ii). 36 degrees; (iii). 72 degrees; (iv). 144 degrees; (v). 288 degrees

4.3.4 Vection magnitude under constant rms velocity

Under constant rms velocity, the following shows the medians of the vection magnitude ratings for five levels of rms velocities: (i) 8 deg./s, (ii) 16 deg./s, (iii) 32 deg./s, (iv) 64 deg./s, (v) 128 deg./s. In the figures, the upper horizontal axes represent oscillation amplitude (degree) and the lower horizontal axes represent frequency (Hz). Oscillation amplitude and frequency were inversely proportional to each other in the same rms velocity. The horizontal double-sided arrows indicate significant differences in the two conditions ($p<0.05$, Wilcoxon). Results show that the vection magnitude decreased significantly as the frequency (or rms velocity) increased when rms velocity was fixed at lower than 32 deg./s. When the rms velocity was fixed at 32 deg./s, the vection magnitude remained unchanged irrespective of increase or decrease in frequency. When the rms velocity was fixed at higher than 32 deg./s, the vection magnitude increased as frequency (or rms velocity) increased.





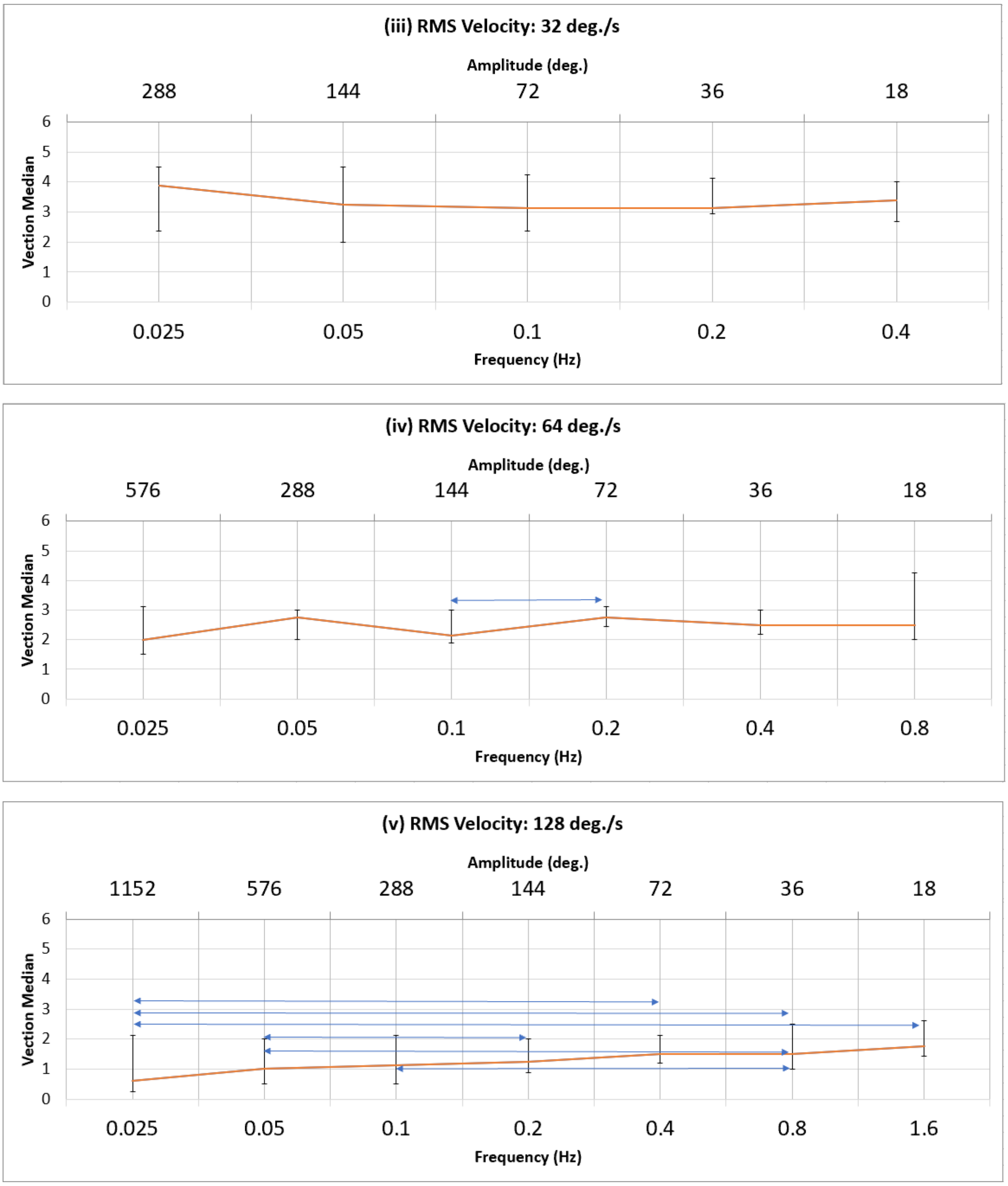


Figure 4.3 Medians of vection magnitude ratings under constant rms velocity in Experiment 1 for five levels of rms velocities: (i). 8 deg./s; (ii). 16 deg./s; (iii). 32 deg./s; (iv). 64 deg./s; (v). 128 deg./s.

4.3.5 Correlation of vection magnitude and electronic games experience

The association between average vection for each subject and electronic games experience of subjects were analyzed. The relationship between vection magnitude and electronic games experience was statistically non-significant (rho = -0.022, p = 0.936, Spearman).

4.3.5 Correlation of vection magnitude and on-set time

The average of on-set time (the time between signal oscillation shown and subjects reported vection) in this experiment is 13.29s and standard deviation of on-set time is 1.19s. The relationship between vection magnitude and on-set time was statistically non-significant (rho = -0.055, p = 0.061, Spearman).

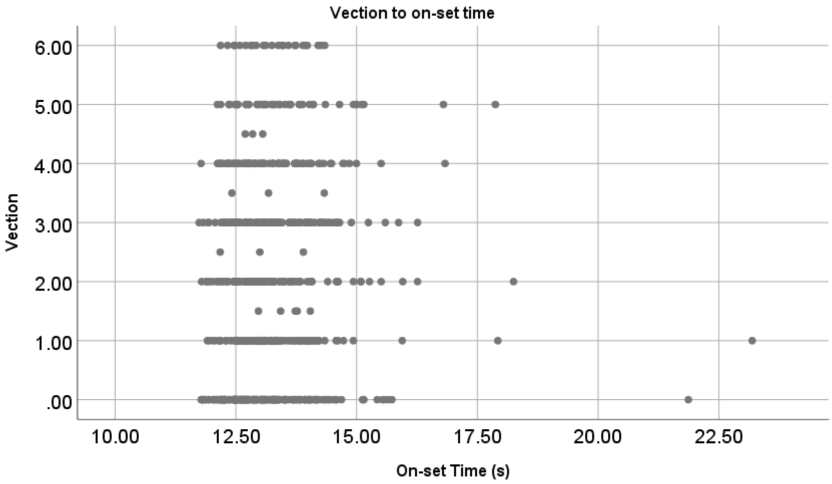


Figure 4.4 Vection under different On-set time in experiment 1

4.3.6 Discussions

The results of this experiment show that the vection magnitudes decreased as the rms velocity (or amplitude) increased when frequency was fixed, and the vection magnitude decreased as the oscillation frequency increased when the oscillation amplitude was fixed. When the rms velocity was fixed at a low magnitude (below 32 deg./s), the vection magnitude decreased as the oscillation frequency increased. When the rms velocity was fixed at 32 deg./s, the vection was constant irrespective of increase or decrease in frequency. When the rms velocity was fixed at a higher magnitude, the vection magnitude increased as the oscillation frequency increased. In the previous relevant findings (Fu, 2017), the vection magnitude increased as the oscillation rms velocity increased or presented an inverted U-shape as the oscillation rms velocity increased when oscillation frequencies were kept constant. When oscillation amplitudes were fixed, the frequency response for vection magnitude presented an inverted U-shape. Comparing the result of this experiment and Fu (2017)'s yaw vection experiment, some differences were found. It was also found that the result of this experiment is closer to Fu's Experiment 2. Both the vection magnitudes decreased as the rms velocity increased when the frequency or the amplitude were fixed, and both the vection magnitudes decreased as frequency increased when the velocities were fixed at low value. Comparing Fu's Experiments 1 and 2, the effect of scene complexity on vection magnitude was hypothesized and was tested in Experiment 2.

The result of this experiment supported TFH (Chen 2014). When frequency was manipulated by varying the rms velocity and keeping the amplitude constant, frequency response for vection magnitude decreased as frequency increased. When frequency was manipulated by varying the amplitude and keeping the rms velocity constant at a low magnitude, frequency response for vection magnitude decreased as frequency increased. When a higher fixed rms velocity was applied, the frequency responses for vection magnitude were inverted.

Chapter 5: Frequency responses of vection when viewing vertical-stripes oscillating along yaw axis:
Keeping rms velocity constant VS Keeping amplitude constant

This chapter describes Experiment 2 that studied the effect of scene complexity on frequency responses of yaw vection. This experiment focused on four situations: fixed rms velocity at 32, 128deg./s and fixed amplitude at 72, 288 degrees. Each situation consisted of at least five levels of frequency (0.025, 0.05, 0.1, 0.2, and 0.4 Hz). The experiment consisted of four repeated sessions with at least 12-hour intervals adopting a within-subject design. Sixteen subjects (9 males, 7 females) who participated in the experiment. The disco light was changed from white square dots to white stripes, so the vertical scene complexity was lower. The disco light alternatively oscillated sinusoidally. Compared to the results of Experiment 1, there were not significate changes in the results of Experiment 2. Therefore, the effect of scene complexity on vection magnitude could not be determined through this experiment. When the oscillation amplitude was fixed, the vection magnitude decreased as frequency increased. When the rms velocity was fixed at 32 deg./s and the frequency was between 0.05 and 0.5Hz, the vection magnitude was constant. When the rms velocity was fixed at 128 deg./s, the vection magnitude increased as the frequency increased.

5.1 Research Gaps and Objectives

Comparing the results of Experiment 1 and the previous related research (Fu 2017), different frequency response of vection magnitude for the two experiments were found. Striped pattern was used as stimulus by Fu and square dot disco light was used as stimulus in Experiment 1. Thus, effect of vertical scene complexity on vection magnitude was hypothesized. In this experiment, the disco light was changed from a square dot pattern to a striped pattern. Frequency response of vection magnitude in this experiment would be compared with Fu's results and results of Experiment 1.

5.2 Methods

5.2.1 Participants

Sixteen subjects (7 females and 9 males) aged between 18 to 23 years (average of 20 years old) participated in the experiment and completed all the repeated sessions in Experiment 2. All the participants passed the line length estimation test with R-square greater than 0.9 before the experiments began. All the participants had normal or correct-to-normal visual acuity. They all signed a consent form voluntarily before the experiment began. All the participants filled the Motion Sickness Susceptibility Questionnaire Short-form (MSSQ-Short) to find out how susceptible they were to motion sickness (Golding, 1998; Golding, 2006). An average percentile score of 48.02% indicated that the sample was slightly insusceptible.

5.2.2 Apparatus and stimulus

Experiment 2 used disco light with stripes as stimulus. The participants wore HTC VIVE goggles to be exposed to the virtual room with disco light.

5.2.3 Experimental design

Similar to Experiment 1, Experiment 2 also had three independent variables: (i) amplitude of visual motion oscillations; (ii) velocity of visual motion oscillation; (iii) repetition. Due to the three-way relationship of amplitude, velocity and frequency ($v = \sqrt{2}\,\pi$ fA), combinations of velocity and amplitude form a many-to-one relationship with the frequency of the visual oscillations. This experiment focused on four situations: fixed rms velocity at 32, 128deg./s and fixed amplitude at 72, 288 degrees. There were 20 conditions for these four situations. The following table presents all the 20 conditions with different combinations of amplitude, velocity and frequency.

Table 5.1 List of conditions in Experiment 2

Con #	freq (Hz)	rms v (deg./s)	amp (deg.)	Con #	freq (Hz)	rms v (deg./s)	amp (deg.)
8	0.4	32	18	26	0.2	128	144
10	1.6	128	18	28	0.00625	8	288
14	0.2	32	36	29	0.0125	16	288
16	0.8	128	36	30	0.025	32	288
17	0.025	8	72	31	0.05	64	288
18	0.05	16	72	32	0.1	128	288
19	0.1	32	72	33	0.2	256	288
20	0.2	64	72	34	0.4	512	288
21	0.4	128	72	36	0.05	128	576
24	0.05	32	144	37	0.025	128	1152

In this experiment, the perceived vection magnitude and perceived speed were assumed as dependent variables. Vection magnitude was measured by a 7-point Likert scale ranging from 0 to 6. Perceived speed was measured by the ratio-scale method with reference condition – Con #19. The reference condition was the middle of the amplitude range (72 deg.), the middle of the rms velocity range (32 deg./s) and the middle of frequency range (0.1 Hz). The average speed of the reference condition was assigned as 1, and there were nine choices of ratios provided: 1/16, 1/8, 1/4, 1/2, 1, 2, 4, 8, and 16.

5.2.4 Experiment procedures

All participants needed to pass the visual acuity test and the line length estimation test and then the training sessions were conducted. In the training session, participants were instructed about their task and exposed to three training conditions for pilot sessions.

There were four repeated sessions for each participant. In each session, participants filled the pre-exposure Simulator Sickness Questionnaire (SSQ) before the session began. If the total pre-SSQ score was larger than 7.48, the session was scheduled to another date (Stanney et al., 2002). When the session started, participants were exposed to all 20 conditions in random order. The 20 conditions were divided into two groups. Each group consisted of 10 conditions. In each group, participants completed the 10 conditions successively. Between each group, there was a 10-minute rest at least until no symptoms were 'Moderate' in SSQ. At the end, participants filled the post-exposure Simulator Sickness Questionnaire (SSQ).

For each condition, the disco light was turned off for 5 seconds. Then, the participants were exposed to the reference oscillation for 20 seconds. Next, the disco light was turned off again for 5 seconds. Last, the participants were exposed to a signal oscillation and they reported perceived speed and vection orally. After the participants had reported the perceived speed and vection, the next condition started.

5.3 Results

5.3.1 Learning effects

The following shows the descriptive statistics for vection magnitudes for the four repetitions. The mean of the vection magnitudes decreased in the first three repetitions and increased in the fourth repetition. Therefore, learning effects were tested first.

Table 5.2 Statistics for vection magnitude in 4 repetitions of Experiment 2

Repetition	Mean	Standard deviation	Minimum	25th percentile	Median	75th percentile	Maximum
1	2.11	1.80	0	0	2	3	6
2	2.19	1.74	0	1	2	3	6
3	2.12	1.75	0	1	2	3	6
4	2.10	1.79	0	0	2	3	6

The perceived vection magnitudes were not normally distributed ($p<0.001$, Shapiro-Wilk). Thus, non-parametric tests were adopted here. Results showed that repetitions had a non-significant influence on vection for four repetitions ($p= 0.541$, Friedman). However, Repetitions 1 and 2 were excluded since Experiment 1 and Fu's experiment also excluded Repetitions 1 and 2. When the data from Repetitions 1 and 2 were excluded, there were also no learning effects ($p= 0.854$, Friedman). Therefore, the subsequent analysis was based on the average ratings of Repetitions 3 and 4 for each participant with respect to each condition.

5.3.2 Vection magnitude under constant amplitude

Under constant oscillation amplitude, the following shows the medians of the vection magnitude ratings for two levels of amplitudes: (i) 72 degrees, (ii) 288 degrees. In the figures, the upper horizontal axes represent the rms velocity (deg./s) and the lower horizontal axes represent frequency (Hz). The rms velocity and frequency were proportional to each other in the same amplitude. The horizontal double-sided arrows indicate significant differences in the two conditions ($p<0.05$, Wilcoxon). Results show that the vection magnitude decreased significantly as the frequency (or rms velocity) increased.

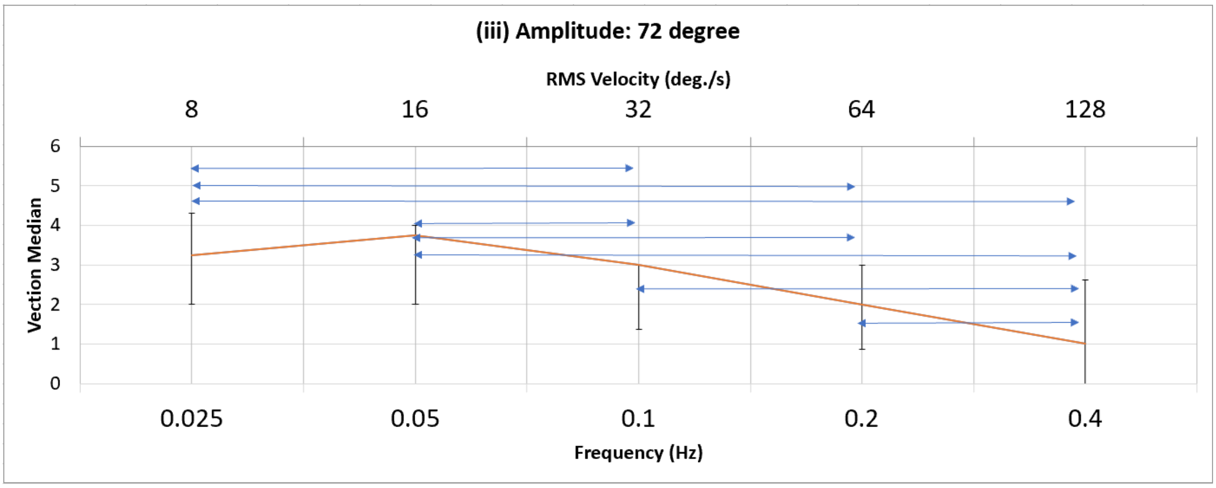


Figure 5.1 Medians of vection magnitude ratings under constant amplitude 72 degrees in Experiment 2

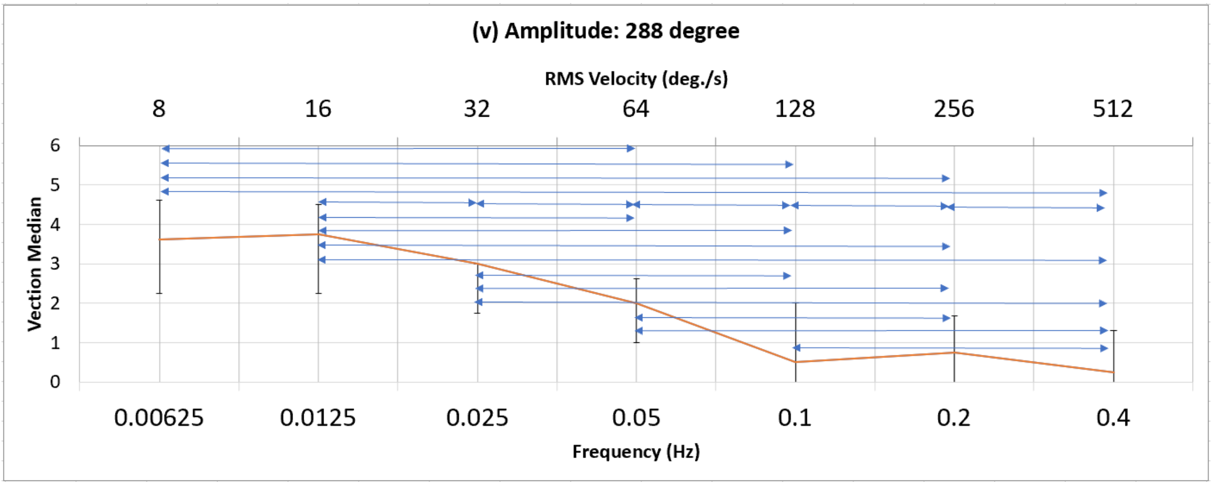


Figure 5.2 Medians of vection magnitude ratings under constant amplitude 288 degrees in Experiment 2

5.3.3 Vection magnitude under constant rms velocity

Under constant rms velocity, the following shows the medians of the vection magnitude ratings for five levels of rms velocities: (i) 32 deg./s, (ii) 128 deg./s. In the figures, the upper horizontal axes represent the oscillation amplitude (degree) and the lower horizontal axes represent frequency (Hz). Oscillation amplitude and frequency were inversely proportional to each other in the same rms velocity. The horizontal double-sided arrows indicate significant differences in the two conditions ($p<0.05$, Wilcoxon). Results show that the vection magnitude decreased significantly as frequency (or rms velocity) increased when the rms velocity was fixed at 128 deg./s. When the rms velocity was fixed at 32 deg./s, the vection magnitude increased between 0.025Hz and 0.05Hz frequency and was constant at other frequencies.

When the rms velocity is fixed, changes of frequency or amplitude are co-founded, and these changes will directly affect the rate of contrasted edges. Our results demonstrated significant changes in vection resulting on fundamentally changes of frequency responses. This is consistently with the hypothesis that changes of perceived ERA is one of the major factors for vection (Hu et al. ,1989; Hettinger, Owen, & Warren, 1985).

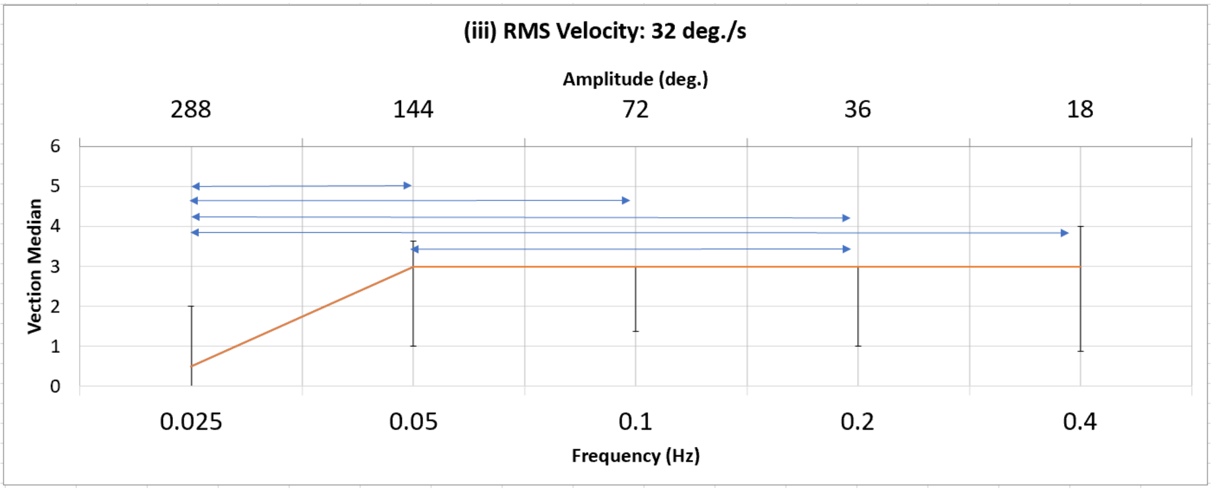


Figure 5.3 Medians of vection magnitude ratings under constant rms velocity 32 deg./s in Experiment 2

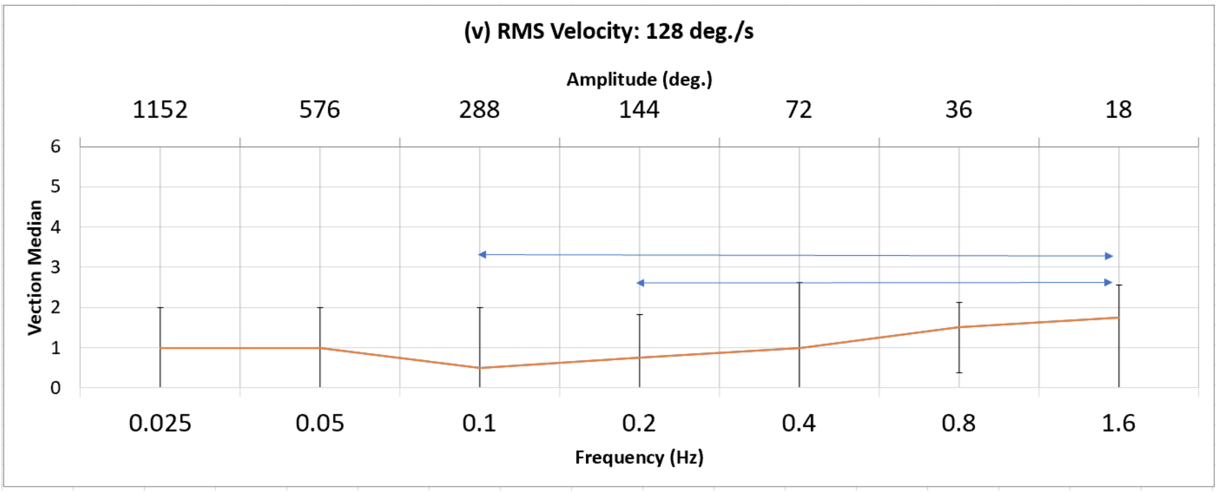


Figure 5.4 Medians of vection magnitude ratings under constant rms velocity 128 deg./s in Expeiment 2

5.3.4 Correlation of vection magnitude and electronic games experience

The association between average vection for each subject and electronic games experience of subjects were analyzed. The relationship between vection magnitude and electronic games experience was statistically non-significant (rho = 0.133, p = 0.622, Spearman).

5.3.5 Correlation of vection magnitude and estimated on-set time

The average of on-set time (the time between signal oscillation shown and subjects reported vection) in this experiment is 13.23s and standard deviation of on-set time is 1.04s. The relationship between vection magnitude and on-set time was statistically non-significant (rho = 0.062, p = 0.120, Spearman).

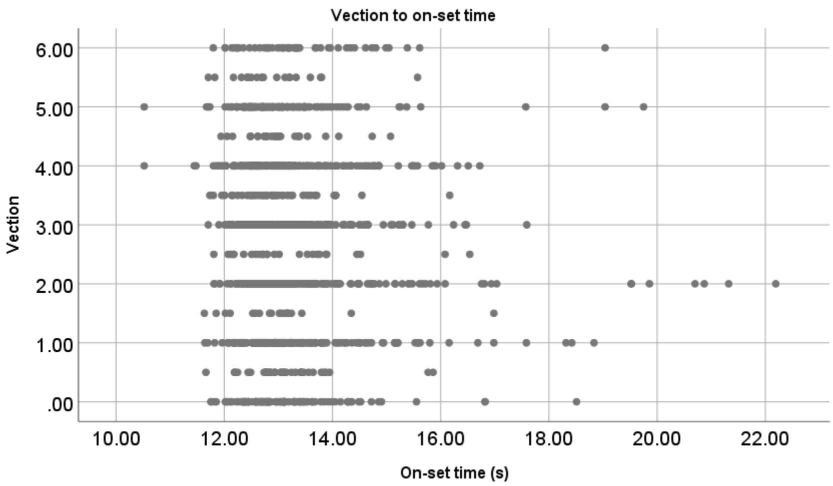


Figure 5.5 Vection under different On-set time in experiment 2

5.3.6 Discussions

The results of this experiment show that there were no significate changes on the shapes of the frequency response curve of vection magnitudes compared to Experiment 1. However, the peak of the vection was shifted from 0.025Hz to 0.05Hz when amplitude was fixed at 72 degree. More conditions were necessary to determine the shifting of frequency response curve.

By Fu (2017)'s result, the peak of curve was located at 0.1Hz when amplitude was fixed at 72 degree and the peak of curve was located at 0.025Hz and 0.05Hz when amplitude was fixed at 288 degree. Frequency responses of vection with fixed amplitude in experiment 2 were shift to left-hand side when it is compared with Fu (2017)'s results. Further work to find out the reason for the differences in findings is required.

The vection magnitude increased as frequency increased when rms velocity was kept constant at 128deg./s. When the rms velocity was fixed at 32 deg./s, vection magnitude was kept constant between 0.05 and 0.4Hz frequency. Vection magnitude increased as frequency changed from 0.025Hz to 0.05Hz. Since the conditions with lower frequency had not been tested in Experiment 1, the shifting of the frequency response curve when rms velocity was fixed at 32 deg./s cannot be supported.

Chapter 6: Conclusions and Limitations

6.1 Conclusions

In summary, this thesis concludes that the frequency response for vection still supported the two-frequency-response hypothesis when a head-mounted immersive stereo VR environment was used as visual stimuli. Under constant rms velocity, yaw vection decreased as frequency increased; under constant low rms velocity, yaw vection decreased as frequency increased; and under constant high rms velocity, yaw vection increased as frequency increased.

Analyses of the effects of rms velocity, vection magnitude was decreasing as velocity increasing. Theses indicated that the larger the rms velocity, the weaker the yaw vection.

There were some effects of vertical scene complexity on vection in yaw axis, but more conditions were necessary for analyzing these effects. Further studies are desirable.

Scene complexity was not the only factor leading to the different results between Experiment 1 and Fu's yaw vection experiment.

6.2 Limitations

There are some limitations in this research: only five frequencies were investigated in each amplitude and rms velocity level. A wider frequency range in each level may be helpful for the shift in the frequency response curve.

Only square dotted and striped disco light patterns were taken into account. A significant change may be found with more random or more complex stimuli patterns.

Only young participants (aged between 18 to 35 years) were included in the current study. Since it has been suggested that Visually induced motion sickness severity can present in all ages, the current results may not be generalized with respect to rest of the population such as older people or children.

Only the sitting postures with chin-rest was studied in the research. Vection may be changed if subjects sit similar to those who play computer games.

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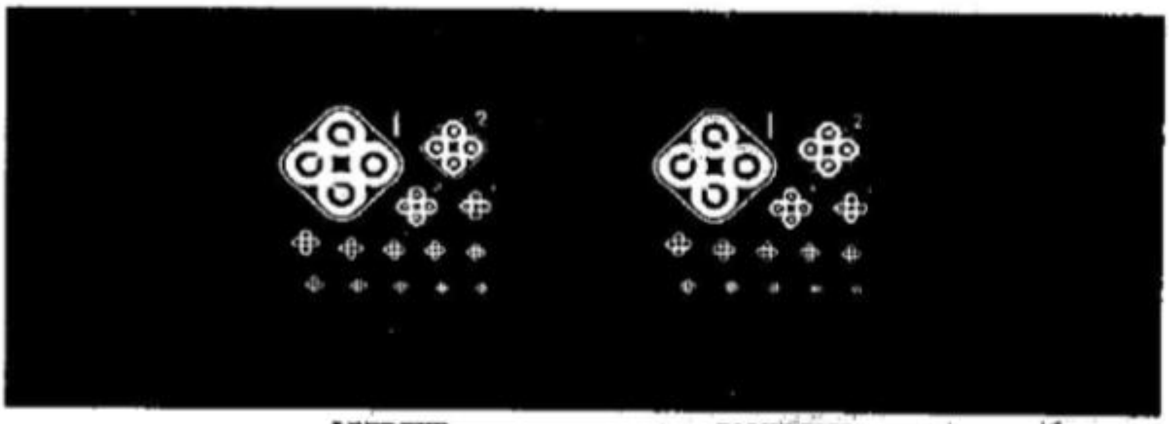
APPENDIX 3.1: Instructions of Measuring Visual Acuity at Near Point by an "Optec®2000" Visual Tester (adopted from Stereo Optical Corp.)

TEST NO. 9 ACUITY BOTH EYES "NEAR"

1. NEAR/FAR Point Switch in the Down position
2. Right and Left eye Switches in the Down position
3. Dial #9 at Blue Indicator (Near)

This test stimulates near vision at a 14 inch distance. Both eyes see the same targets which are fused into a single target when viewed binocularly.

QUESTION: "Look at the #1 target. Is the ring at the RIGHT broken like the other rings or is it unbroken? Where is the unbroken ring in target #4–at the top, bottom, right or left? #5? #6? Score these tests the same as FAR acuity tests. Record last correct answer after two consecutive misses.



LEFT EYE RIGHT EYE

SCORE	1	2	3	4	5	6	7	8	9	10	11	12	13	14
KEY	R	L	T	R	B	R	T	L	T	L	B	R	B	L
	20	20	20	20	20	20	20	20	20	20	20	20	20	20
	200	100	70	50	40	35	30	25	22	20	18	17	15	13

Left = ←, Right = →, Top = ↑, Bottom = ↓

APPENDIX 3.2: Motion Sickness Susceptibility Questionnaire Short-Form (MSSQ) and the Scoring Method (Adopted from Golding, 1998)

1. Please State Your **Age** .... Years. *2.* Please State Your Sex (tick box) **Male** [ ] **Female** [ ]

This questionnaire is designed to find out how susceptible to motion sickness you are, and what sorts of motion are most effective in causing that sickness. Sickness here means feeling queasy or nauseated or actually vomiting.

Your CHILDHOOD Experience Only (before 12 years of age), for each of the following types of transport or entertainment please indicate:

3. **As a CHILD (before age 12),** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	Never Felt Sick	Rarely Felt Sick	Sometimes Felt Sick	Frequently Felt Sick
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					

Your Experience over the LAST 10 YEARS (approximately), for each of the following types of transport or entertainment please indicate:

4. **Over the LAST 10 YEARS,** how often you **Felt Sick or Nauseated** (tick boxes):

	Not Applicable - Never Travelled	Never Felt Sick	Rarely Felt Sick	Sometimes Felt Sick	Frequently Felt Sick
Cars					
Buses or Coaches					
Trains					
Aircraft					
Small Boats					
Ships, e.g. Channel Ferries					
Swings in playgrounds					
Roundabouts in playgrounds					
Big Dippers, Funfair Rides					

Scoring the MSSQ- Short

Section A (Child) (Question 3)

Score the number of types of transportation not experienced (i.e., total the number of ticks in the 't' column, maximum is 9).

Total the sickness scores for each mode of transportation, i.e. the nine types from 'cars' to 'big dippers' (use the 0-3 number score key at bottom, those scores in the 't' column count as zeroes).

MSA = (total sickness score child) x (9) / (9 - number of types not experienced as a child)

Note 1. Where a subject has not experienced any forms of transport a division by zero error occurs. It is not possible to estimate this subject's motion sickness susceptibility in the absence of any relevant motion exposure.
Note 2. The Section A (Child) score can be used as a pre-morbid indicator of motion sickness susceptibility in patients with vestibular disease.

Section B (Adult) (Question 4)

Repeat as for section A but using the data from section B.

MSB = (total sickness score adult) x (9) / (9 - number of types not experienced as an adult)

Raw Score MSSQ-Short

Total the section A (Child) MSA score and the section B (Adult) MSB score to give the MSSQ-Short raw score (possible range from minimum 0 to maximum 54, the maximum being unlikely)

MSSQ raw score = MSA + MSB

Percentile Score MSSQ-Short

The raw to percentile conversions are given below in the Table of Statistics & Figure, use interpolation where necessary.

Alternatively a close approximation is given by the fitted polynomial where y is percentile; x is raw score
$y = a.x + b.x^2 + c.x^3 + d.x^4$
a = 5.1160923 b = -0.055169904
c = -0.00067784495 d = 1.0714752e-005

Table of Means and Percentile Conversion Statistics for the MSSQ-Short (n=257)

Percentiles Conversion	Raw Scores MSSQ-Short		
	Child Section A	Adult Section B	Total A+B
0	0	0	0
10	.0	.0	.8
20	2.0	1.0	3.0
30	4.0	1.3	7.0
40	5.6	2.6	9.0
50	7.0	3.7	11.3
60	9.0	6.0	14.1
70	11.0	7.0	17.9
80	13.0	9.0	21.6
90	16.0	12.0	25.9
95	20.0	15.0	30.4
100	23.6	21.0	44.6
Mean	7.75	5.11	12.90
Std. Deviation	5.94	4.84	9.90

Table note: numbers are rounded

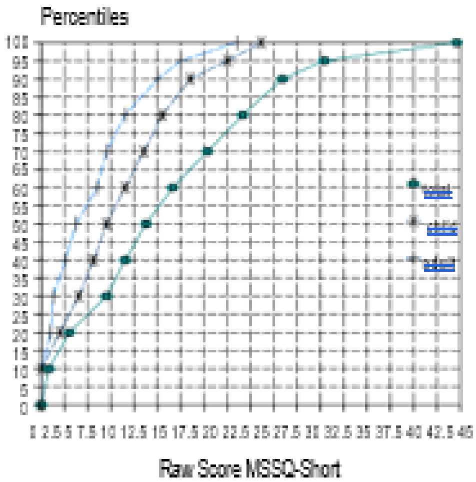


Figure: Cumulative distribution Percentiles of the Raw Scores of the MSSQ-Short (n=257 subjects).

Reference Note

For more background information and references to the original Reason & Brand MSSQ and to its revised version the 'MSSQ-Long', see:

Golding JF. Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness. **Brain Research Bulletin**, 1998; 47: 507-516.
Golding JF. (2006) Predicting Individual Differences in Motion Sickness Susceptibility by Questionnaire. **Personality and Individual differences, 41**: 237-248.

APPENDIX 3.3: SIMULATOR SICKNESS QUESTIONNAIRES (SSQ)

Pre-exposure instructions: please fill in this questionnaire. Circle below if any of the symptoms apply to you now. You will be asked to fill this again after the experiment

一般不適	1. General discomfort	None	Slight		Moderate	Severe	
疲 倦	2. Fatigue	None	Slight		Moderate	Severe	
沉 悶	3. Boredom	None	Slight		Moderate	Severe	
想 睡	4. Drowsiness	None	Slight		Moderate	Severe	
頭 痛	5. Headache	None	Slight		Moderate	Severe	
眼 痛	6. Eyestrain	None	Slight		Moderate	Severe	
很難集中視力	7. Difficulty focusing	None	Slight		Moderate	Severe	
口水分秘增加	8. Salivation increase	None	Slight		Moderate	Severe	
口水分秘減少	Salivation decrease	None	Slight		Moderate	Severe	
出 汗	9. Sweating	None	Slight		Moderate	Severe	
作 嘔	10. Nausea	None	Slight		Moderate	Severe	
很難集中精神	11. Difficulty concentrating	None	Slight		Moderate	Severe	
精神的壓抑	12. Mental depression		No	Yes (	Slight	Moderate	Severe)
頭 脹	13. "Fullness of the head"		No	Yes (	Slight	Moderate	Severe)
視野模糊	14. Blurred vision		No	Yes (	Slight	Moderate	Severe)
眼 花 (開)	15. Dizziness eyes open		No	Yes (	Slight	Moderate	Severe)
眼 花 (合)	Dizziness eyes close		No	Yes (	Slight	Moderate	Severe)
眩 暈	16. Vertigo		No	Yes (	Slight	Moderate	Severe)
幻 覺	17. Visual flashbacks*		No	Yes (	Slight	Moderate	Severe)
昏 厥	18. Faintness		No	Yes (	Slight	Moderate	Severe)
呼 吸 異 樣	19. Aware of breathing		No	Yes (	Slight	Moderate	Severe)
胃感覺異樣	20. Stomach awareness		No	Yes (	Slight	Moderate	Severe)
沒 有 胃 口	21. Loss of appetite		No	Yes (	Slight	Moderate	Severe)
胃 口 增 加	22. Increased appetite		No	Yes (	Slight	Moderate	Severe)
想去洗手間	23. Desire to move bowels		No	Yes (	Slight	Moderate	Severe)
迷 惘	24. Confusion		No	Yes (	Slight	Moderate	Severe)
打 嗝	25. Burping		No	Yes (	Slight	Moderate	Severe)
嘔 吐	26. Vomiting		No	Yes (	Slight	Moderate	Severe)
其 他	27. Other		No	Yes (	Slight	Moderate	Severe)

APPENDIX 3.4: The Calculations in the Simulator Sickness Questionnaire

None = 0

Slight = 1

Moderate = 2

Severe = 3

Weights for Symptoms

Symptoms	Nausea	Oculomotor	Disorientation
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eye strain		1	
Difficulty focusing		1	1
Increased salivation	1		
Sweating	1		
Nausea	1		1
Difficulty concentrating	1	1	
Fullness of head			1
Blurred vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach awareness	1		
Burping	1		
Total	[1]	[2]	[3]

Score:

Nausea = [1] * 9.54

Oculomotor = [2] * 7.58

Disorientation = [3] * 13.92

Total Score = ([1] + [2] + [3]) *3.74

APPENDIX I: Results of Friedman Test—Effects of Repeated Trial on Vection Magnitude with Same Condition and Same Subject

Noted: Highlighted cells mean the p-value is larger than 0.05. There is no learning effect during these repetition sessions.

Result of p-values using Friedman Test for Experiment 1:

Included repetition sessions	p-values
1, 2, 3, 4	0
2, 3, 4	0.001
3, 4	0.362

Result of p-values using Friedman Test for Experiment 2:

Included repetition sessions	p-values
1, 2, 3, 4	0.216
2, 3, 4	0.195
3, 4	0.449

APPENDIX II: Results of Wilcoxon Signed Rank Test—Effects of RMS Velocity on Vection under Constant Frequency for Experiment 1

Noted: Highlighted cells indicate significant differences in two conditions ($p<0.05$, Wilcoxon).

RMS Velocity (deg./s)		Fixed Frequency (Hz)				
Velocity_1	Velocity_2	0.025	0.05	0.1	0.2	0.4
128	2	0.002				
64	2	0.002				
32	2	0.031				
16	2	0.113				
8	2	0.207				
4	2	0.010				
128	4	0.004	0.007			
64	4	0.004	0.021			
32	4	0.343	0.335			
16	4	0.905	0.751			
8	4	0.655	0.424			
512	8					0.006
256	8				0.006	0.008
128	8	0.004	0.007	0.003	0.011	0.034
64	8	0.001	0.013	0.015	0.033	0.080
32	8	0.034	0.185	0.635	0.720	0.823
16	8	0.526	0.837	0.906	0.113	0.964
512	16					0.006
256	16				0.009	0.006
128	16	0.003	0.007	0.008	0.010	0.035
64	16	0.003	0.007	0.010	0.067	0.155
32	16	0.065	0.175	0.574	0.598	0.782
512	32					0.006
256	32				0.007	0.006
128	32	0.003	0.006	0.005	0.012	0.013
64	32	0.003	0.025	0.014	0.035	0.022
512	64					0.007
256	64				0.006	0.007
128	64	0.016	0.010	0.003	0.012	0.035
512	128					0.002
256	128				0.008	0.030
512	256					0.019

APPENDIX III: Results of Wilcoxon Signed Rank Test—Effects of Frequency on Vection under Constant Amplitude for Experiment 1

Noted: Highlighted cells indicate significant differences in two conditions (p<0.05, Wilcoxon).

Frequency (Hz)		Fixed Amplitude (Degree)				
Freq_1	Freq_2	18	36	72	144	288
0.4	0.00625					0.837
0.2	0.00625					0.139
0.1	0.00625					0.008
0.05	0.00625					0.021
0.025	0.00625					0.229
0.0125	0.00625					0.270
0.4	0.0125				0.006	0.206
0.2	0.0125				0.010	0.006
0.1	0.0125				0.003	0.011
0.05	0.0125				0.008	0.143
0.025	0.0125				0.138	0.725
1.6	0.025	0.012				
0.8	0.025	0.002	0.007			
0.4	0.025	0.016	0.005	0.055	0.006	0.339
0.2	0.025	0.001	0.066	0.648	0.008	0.007
0.1	0.025	0.001	0.053	0.345	0.003	0.009
0.05	0.025	0.001	0.149	0.447	0.005	0.054
1.6	0.05	0.041				
0.8	0.05	0.055	0.008			
0.4	0.05	0.648	0.021	0.090	0.007	0.016
0.2	0.05	0.345	0.229	0.916	0.013	0.005
0.1	0.05	0.447	0.270	0.602	0.025	0.008
1.6	0.1	0.032				
0.8	0.1	0.090	0.011			
0.4	0.1	0.916	0.143	0.122	0.011	0.008
0.2	0.1	0.602	0.725	0.392	0.039	0.009
1.6	0.2	0.059				
0.8	0.2	0.122	0.009			
0.4	0.2	0.392	0.054	0.009	0.006	0.037
1.6	0.4	0.016				
0.8	0.4	0.009	0.008			
1.6	0.8	0.062				

APPENDIX IV: Results of Wilcoxon Signed Rank Test—Effects of Frequency on Vection under Constant RMS Velocity for Experiment 1

Noted: Highlighted cells indicate significant differences in two conditions ($p < 0.05$, Wilcoxon).

Frequency (Hz)		Fixed rms velocity (Deg./s)				
Freq_1	Freq_2	8	16	32	64	128
0.4	0.00625	0.059				
0.2	0.00625	0.051				
0.1	0.00625	0.017				
0.05	0.00625	0.067				
0.025	0.00625	0.549				
0.0125	0.00625	0.718				
0.4	0.0125	0.027	0.037			
0.2	0.0125	0.009	0.006			
0.1	0.0125	0.001	0.011			
0.05	0.0125	0.008	0.012			
0.025	0.0125	0.209	0.213			
1.6	0.025					0.013
0.8	0.025				0.414	0.016
0.4	0.025	0.126	0.122	0.779	0.469	0.040
0.2	0.025	0.091	0.009	0.365	0.309	0.148
0.1	0.025	0.009	0.025	0.057	0.565	0.487
0.05	0.025	0.139	0.083	0.113	0.686	0.453
1.6	0.05					0.051
0.8	0.05				0.646	0.011
0.4	0.05	0.350	0.324	0.538	0.794	0.063
0.2	0.05	0.387	0.044	0.596	0.261	0.046
0.1	0.05	0.095	0.206	0.604	0.473	0.602
1.6	0.1					0.108
0.8	0.1				0.206	0.046
0.4	0.1	0.894	0.927	0.327	0.459	0.150
0.2	0.1	0.506	0.623	0.281	0.031	0.217
1.6	0.2					0.092
0.8	0.2				0.619	0.358
0.4	0.2	0.887	0.813	0.831	0.283	0.265
1.6	0.4					0.560
0.8	0.4				0.892	0.916
1.6	0.8					0.458

APPENDIX V: Results of Wilcoxon Signed Rank Test—Effects of Frequency on Vection under Constant Amplitude for Experiment 2

Noted: Highlighted cells indicate significant differences in two conditions ($p<0.05$, Wilcoxon).

Frequency (Hz)		Fixed Amplitude (Degree)				
Freq_1	Freq_2			72		288
0.4	0.00625					0.001
0.2	0.00625					0.001
0.1	0.00625					0.006
0.05	0.00625					0.018
0.025	0.00625					0.095
0.0125	0.00625					0.968
0.4	0.0125					0.001
0.2	0.0125					0.001
0.1	0.0125					0.001
0.05	0.0125					0.001
0.025	0.0125					0.003
1.6	0.025					
0.8	0.025					
0.4	0.025			0.007		0.001
0.2	0.025			0.026		0.001
0.1	0.025			0.035		0.002
0.05	0.025			0.721		0.003
1.6	0.05					
0.8	0.05					
0.4	0.05			0.006		0.002
0.2	0.05			0.020		0.014
0.1	0.05			0.032		0.012
1.6	0.1					
0.8	0.1					
0.4	0.1			0.008		0.027
0.2	0.1			0.080		0.726
1.6	0.2					
0.8	0.2					
0.4	0.2			0.041		0.015
1.6	0.4					
0.8	0.4					
1.6	0.8					

APPENDIX VI: Results of Wilcoxon Signed Rank Test—Effects of Frequency on Vection under Constant RMS Velocity for Experiment 2

Noted: Highlighted cells indicate significant differences in two conditions (p<0.05, Wilcoxon).

Frequency (Hz)		Fixed rms velocity (Deg./s)				
Freq_1	Freq_2			32		128
0.4	0.00625					
0.2	0.00625					
0.1	0.00625					
0.05	0.00625					
0.025	0.00625					
0.0125	0.00625					
0.4	0.0125					
0.2	0.0125					
0.1	0.0125					
0.05	0.0125					
0.025	0.0125					
1.6	0.025					0.207
0.8	0.025					0.781
0.4	0.025			0.006		0.874
0.2	0.025			0.006		0.352
0.1	0.025			0.007		0.306
0.05	0.025			0.001		0.588
1.6	0.05					0.094
0.8	0.05					0.441
0.4	0.05			0.401		0.620
0.2	0.05			0.039		0.719
0.1	0.05			0.101		0.084
1.6	0.1					0.022
0.8	0.1					0.094
0.4	0.1			0.365		0.133
0.2	0.1			0.608		0.425
1.6	0.2					0.025
0.8	0.2					0.258
0.4	0.2			0.468		0.380
1.6	0.4					0.062
0.8	0.4					0.854
1.6	0.8					0.088