FREQUENCY RESPONSES OF VISUALLY INDUCED MOTION SICKNESS: ISOLATING EFFECTS OF VELOCITY AND AMPLITUDE OF VISUAL STIMULI

by

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A Thesis Submitted to
The Hong Kong University of Science and Technology
in Partial Fulfillment of the Requirements for
the Degree of Doctor of Philosophy
in Industrial Engineering and Logistics Management

August 2014, Hong Kong

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This is to certify that I have examined the above PhD thesis
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Acknowledgments

My foremost thanks must go to my supervisor, Prof. Richard So. Thank you for your patience when I made mistakes, your advice when I was confused, and your prayers when I was in the darkest moment of my life. From you I learned integrity, generosity, and responsibility. Your wisdom will guide me through the rest of my life. You are my master!

Many thank my thesis committee panel, Prof. Yoshizawa, Prof. Shi, Prof. Hong, and Prof. Mak. Thank you all for your generous and valuable comments. I also must thank Prof. Ravindra Goonetilleke. It's unbelievable that you are a great batsmen!

A special thank must go to Dr. Anton Wei. You are like my big brother in life. The way you led me through this PhD just like the way you led me through all the MacLehose Trails. By the way, you cook nice!

My research group buddies Bao, Buddhika, Coco, Dubo, Thilina, and Zoe. You guys are amazing. I enjoyed every minute discussing research problems and all other interesting stuffs with you. Cheers advanced seminar!

I also want to thank our lab technicians, Denil, Yong, and Tin and our department secretaries, Fona, Joyce, and Vera. Your kind help and support are crucial to the completion of this PhD.

I am also grateful to Ms Sarah Cook and Ms Jill Yang for proofreading. Cheers!

I owe millions of thanks to my family, my mom, Du Fengqian, my dad, Chen Hanying, and my sister, Chen Jinxia. Without your unselfish support and unconditional love, it is impossible for me to get through these uneasy years of PhD. Especially I wish to dedicate this thesis to my dad, who is watching and praying for me in heaven.

Finally, to my dearest wife, Mao Chang. Thank you always being there for me. I knew you made a tough decision when you said "yes I do". But here I promise: Grow old with me. The best is yet to be.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Frequency Responses of Visually Induced Motion Sickness: Isolating Effects of Velocity and Amplitude of Visual Stimuli

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Abstract

Prolonged exposure to wide field-of-view visual motion can cause visually-induced motion sickness (VIMS). Reports on which frequencies of visual motion that will provoke the highest levels of VIMS have been contradicting. An in-depth review suggests that these studies manipulated the frequency of their stimuli in different ways: some kept stimuli's velocity constant while others kept stimuli's amplitude constant. In other words, there may be two types of frequency responses for VIMS depending on whether the velocity or the amplitude of the visual motion was kept constant (referred to as the two-frequency-response hypothesis). In this thesis, four experiments were conducted to test the two-frequency-response hypothesis within the scope of visual motions along the fore-and-aft axis. The first two experiments (Experiment PS1 and PS2) measured the illusive sensation of self-motion (vection) and perceived speed (PS), and the other two experiments (Experiment VIMS1 and VIMS2) measured VIMS directly. These experiments consistently found that there were two different types of frequency responses with VIMS, vection and PS. When the r.m.s. velocity was kept unchanged, the severity of VIMS was independent of frequency and when the amplitude was kept constant, the level of VIMS increased with increasing frequency. Based upon the findings of the experiments, a better method to simplify and unify the presentation of the two types of frequency responses of VIMS was proposed. Moreover, how the current findings relate and fit into the existing literature body was discussed, with an additional application to enhance a previously reported cybersickness dose value (CSDV) model for predicting levels of VIMS.

CHAPTER 1: INTRODUCTION

1.1 Motion Sickness and Visually Induced Motion Sickness (VIMS)

There is an old saying: "when you first get motion sick you fear you're going to die... and then - as it goes on - you start to fear that you won't die!" (citing from www.motion-sickness-guru.com). This statement, to some extent, reflects how serious motion sickness can be. About one third of people would experience moderate levels of motion sickness when they are travelling by air, land, or sea transportation (Griffin, 1990; So *et al.,* 1999). Based on the form of transport, airsickness, carsickness, seasickness are termed as specific forms of motion sickness. Symptoms of motion sickness can range from cold sweating, spatial disorientation to nausea and emesis (Benson, 1990).

With the exponential growth of usages of computer graphics technology in the past decades, incidents of motion sickness caused by prolong exposure to flight simulator training, video games, or 3D films have been reported (Bos *et al*., 2013; Kennedy *et al*., 1989; Solimini, 2013; Stoffregen *et al*., 2008). These types of motion sickness are often termed as visually induced motion sickness (VIMS) since these motion sicknesses have been caused by visual stimuli. In fact, simulator sickness, cybersickness, optokinetic motion sickness and vection-induced motion sickness can be categorized as VIMS because visual motion is presented in the absence of appropriate physical motion in all cases.

1.2 Importance of Visual Image Safety and the Prevalence of VIMS

In the continue quest for “real” sensation and ultimate entertainment, display screens are becoming larger, and video games and (IMAX) movies are becoming more and more realistic and immersive. Nevertheless, the increased prevalence of these advanced technologies accompanies with the increased prevalence of the visual images safety issue, an ever-increasing public concern (Bos, 2011; Ishida *et al*., 1998; So and Ujike, 2010).

The safety issue of images caught the attention of ISO (International Standards Organization) in 2004 and this resulted in an International Workshop Agreement (IWA 3:2005), which recognized

VIMS, visual fatigue, and photosensitive seizures as the major biomedical concerns regarding image safety. Subsequently a bi-annual international symposium series, initiated by Dr. Richard So in 2007, have brought together scientists and industrial partners interested and dedicated in this issue (So *et al*., 2007 – please see the publication list on the conference proceedings VIMS2007 for the full reference). Selected publications from this conference are published as a special issue at the journal of Applied Ergonomics (So and Uijike, 2010).

IWA3 reported that VIMS is one of the major causes of image safety. Sickness symptoms associated with VIMS are known to be reported among viewers of videogames or movies that contain footage taken using a hand-held camera (Merhi *et al*., 2007; Ujike *et al*., 2008). In recent years, VIMS has also been found to cause sickness among viewers of IMAX cinema. Consequently, we need to study the etiology of VIMS. This need is also confirmed in IWA3.

1.3 Preventions and Countermeasures for VIMS

As one-third of the world's population are susceptible to motion sickness, driven by the needs, people try nearly every possibility to release symptoms that bother them. For motion sickness, use of ginger is, perhaps, the most ancient recipe (Langner *et al*., 1998). With advances in science and a better understanding in recent decades, various countermeasures against motion sickness have been invented, developed, and commercialized (e.g., Marcus and Furman, 2006; Miller and Muth, 2004; Nachum *et al*., 2006). A review of literature indicates that most of these anti-motion sickness drugs focused on stopping the neural transmission of signals to the autonomous nerves systems in human which are known to be responsible for triggering a collection of physiological responses such as sweating, increases of breathing rates, increases in heart rates, abnormal electric activities in the stomach, etc. (Ji *et al*., 2005; Spinks *et al*., 2007). This can be understood as these drugs were targeted for travellers who had to complete their motion sickness provoking journeys. In contrast, anti-VIMS measures can be different because we could control, modulate or change the VIMS-provoking stimuli. One example is that we can change the scenes in a video game. However, this is easier said than done. One of the reasons could be that any countermeasures to reduce VIMS may also reduce sensation of apparent self-motion, known as vection which in turn could reduce the "thrill" experience for viewers. Consequently, we need to have an in-depth understanding of the relationships among the characteristics of the VIMS-provoking stimuli, VIMS symptoms and vection.

1.4 Significance of Visual Motion Characteristics for Incidences of VIMS

To solve a problem, intuition is to eliminate it at the source in the first place. Therefore it is of great interest to study VIMS by digging into its source – the visual movements. A VIMS-provoking visual motion is characterized by a number of parameters, such as navigation speed, frequency, motion direction, travel distance and duration, image complexity, etc. The ISO IWA-3 (2005) suggests further research to be conducted to determine the relationships among severity levels of VIMS and these visual motion characteristics. For instance, stimuli moving in roll axis have been known to cause higher sickness, followed by pitch, and then yaw (Lo and So, 2001; Ujike *et al*., 2004). Symptoms usually have an onset time within 15 minutes of the immersion period and continue to increase to severe nausea between 35 to 60 minutes (Cobb *et al*., 1999). Levels of VIMS increase with navigation velocity that lower than 10 m/s, and stabilize beyond (So *et al*., 2001b).

1.4.1 Frequency weightings or responses of VIMS: its importance

Effects of frequency of physical motion on levels of motion sickness among those who were exposed had been the subjects of many studies (e.g., Griffin, 2007). While apparent success to predict motion sickness caused by physical movements has been proved with the use of a frequency weighting (W_f) defined in International Standard 2631 (ISO 2631, 1997) and British Standard 6841 (BS 6841, 1987), there is a lack of standardization of the frequency weighting for VIMS.

There are few studies investigating the relations between frequency of visual motion and VIMS. In 2004, Duh and Parker proposed a cross-over frequency (COF) theory and hypothesized that VIMS should peak around 0.06 Hz. However, Diels and Howarth (2012) claimed to disprove the COF theory by showing that VIMS achieved maximum at 0.2 Hz (instead of 0.06 Hz) when stationary subjects were presented with oscillating visual stimulus in fore-and-aft direction.

1.4.2 Frequency weightings or responses of VIMS: its problems

Not only there is a lack of standardization in frequency weightings in quantifying VIMS-provoking visual stimuli, the effects of oscillation velocity and oscillation amplitude on levels of VIMS had not been studied in isolation. Since by one parameter constant, changing the other parameter can change the frequency of the visual motion, whether changing velocity and amplitude of visual motion would produce the same frequency responses are unknown. This leads to the following two research gaps.

1.5 Research Gaps

[Gap 1] The effects of velocity and amplitude have not been studied in isolation in studies determining the frequency responses of VIMS. In short, changing velocity with constant amplitude may result in different frequency responses from changing amplitude with constant velocity (the two-frequency-response hypothesis).

[Gap 2] Past prediction of VIMS had assumed that there is only one type of frequency weightings. A review of literature indicated that past work on cybersickness dose value (CSDV) has always kept the oscillation amplitude constant (So *et al*., 2001a). It was true that there had been studies on the frequency responses of VIMS with constant velocity but they did not predict VIMS (Duh *et al*., 2004; Diels and Howarth, 2012).

The aim of this thesis was to fill the above research gaps; investigate the causes of VIMS related to the frequency, velocity and amplitude of the visual motion, and ultimately model and predict levels of VIMS using parameters associated with the visual stimuli.

1.6 Thesis Organization

This thesis was divided into 8 chapters, each summarized as follows.

Chapter 1 introduces essential background information about VIMS as a key component in the problem of visual image safety. It also narrows the scope of this thesis by emphasizing the importance of frequency characteristics in altering the severity of VIMS.

Chapter 2 reviews a wide range of literature specialized in frequency responses of VIMS. This chapter provides a bird view over past studies associated with the current topic.

Chapter 3 summarizes the facilities and the apparatus that had been used in the experiments. Some common experimental procedures are also included.

Chapter 4 presents the work of two experiments (Experiment PS1 and PS2) that involved measurements of vection and perceived speed (PS), which investigated the two types of frequency responses of viewers exposed to sinusoidal optic flow in fore-and-aft axis under conditions that either r.m.s. velocity was kept constant, or amplitude was kept constant.

Chapter 5 presents the work of another two experiments (Experiment VIMS1 and VIMS2) that measured VIMS directly to further testify the two-frequency-response hypothesis for VIMS with fore-and-aft stimuli.

Chapter 6 presents a new graphical method to simplify and unify the presentation of results of the two types of frequency responses of VIMS.

Chapter 7 discusses how the findings of this thesis fit into existing literature. Applications of the current results to improve a previous VIMS prediction model are also discussed.

Chapter 8 concludes the main findings and contributions of the present thesis, and further comments on the limitations of the experiments and suggests possible future work.

CHAPTER 2: LITERATURE REVIEW

SUMMARY

The chapter starts with reviews on studies and measurements concerning visually induced motion sickness (VIMS). The major theories on VIMS and the importance of frequency responses of VIMS are also presented.

2.1 Characteristics of Visually Induced Motion Sickness

2.1.1 Definition and Symptoms

Steele (1961) might be the first one to use the term visually induced motion sickness (VIMS) to describe motion sickness-like symptoms observed in static people who are subject to visual stimulation alone.

In general, VIMS is a term that includes, but not limit to, simulator sickness (typically observed in flight and driving simulators; Kennedy *et al*., 1985, 1992a, 1992b, 1993; Kolasinski, 1995, 1996; Cobb *et al*., 1999; Crowley, 1987; Reason and Diaz, 1971), cybersickness (concerning immersion in virtual reality systems; McCauley and Sharkey, 1992; Stanney *et al*., 1997a, 1997b, 1998, 1999; Strauss, 1995; LaViola, 2000; So *et al*., 1999, 2001a, 2001b; Lo and So, 2001;), and Cinerama/Imax sickness (referring to watching movies or motion pictures on a large screen; Benson, 2002; Ujike *et al*., 2008; So and Ujike, 2010; Howarth, 2011). It refers to the phenomenon that when a viewer watches a compelling visual moving scene, usually with large field-of-view, continuously, he or she will feel symptoms of motion sickness such as nausea and stomach awareness (So and Ujike, 2010). In general, about one-third of the Hong Kong Chinese population are susceptible to VIMS, one-third are not susceptible and the rest are in between (So *et al.* 1999).

Recently, ISO (International Standardization Organization) provide a more precise definition of VIMS and quoted: “Visually-induced motion sickness concerns motion sickness-like symptoms induced by motion within the visual environment, such as when watching movies and screen images of videogames. These symptoms may include dizziness, vertigo, sweating, odd feelings in the stomach, and nausea which may progress to vomiting.” (IWA3:2005).

The severity of VIMS can range from mild discomfort for a videogame player to some serious consequences among a large group of audience watching movies. Van der Spek *et al*. (2007) reported that experience of VIMS will affect the affective appraisal towards the usage of virtual environments (VE). Users of VEs who suffered from VIMS typically rated the VE experience to be more sleepy and unpleasant than those who did not suffer from VIMS. Reed *et al*. (2007) found that the drop-out rate of driving simulation training programs due to symptoms of VIMS was up to 50%. This figure was considered by the training industry as unacceptably high and could seriously affect any commercial training program for drivers and pilots. Ujike *et al*. (2008) reported that 36 students out of 294 suffered from nausea and other motion sickness-like symptoms and were sent to the hospital after watching a 20-min movie displayed on a large screen. The movie was captured by a handheld camera, which induced unexpected whole image vibration and motion.

It is in the interest among the developers of VEs, producers of movies, and computer game developers to ensure that the advancement of technology does not come at the expense of the physical well-being of the users. One of the concluding remarks at the ISO International Worshop Agreement (IWA3) was that research into the mechanism of VIMS deserves more attention. .

2.1.2 Measurements

“What gets measured, gets managed.” Learning from the wisdom of the American management guru -- Peter Drucker, we know that if we want to control and counteract VIMS, first we have to measure it. Measuring the symptoms of a person under exposure of virtual environments or simulators is a challenging task because VIMS is polysymptomatic and large individual differences exist (McCauley and Sharkey, 1992; Kolasinski, 1995; Kennedy and Fowlkes, 1992).

Existing methods of measuring VIMS can be mainly divided into two categories: subjective measurements and objective measurements.

2.1.2.1 Subjective Measurements

Typically, subjective measurements of VIMS are self-reports on the severity of the symptoms according to some well-designed questionnaires or surveys. The most popular one is the Simulator Sickness Questionnaire (SSQ) developed by Kennedy, Lane, Berbaum, and Lilienthal (1993). The SSQ contains a checklist of 28 symptoms derived from the Pensacola Motion Sickness Questionnaire (MSQ; Kellogg *et al*., 1965). Each of the symptoms is rated in terms of presence or severity with a 4-point Likert Scale (0: none; 1: slight; 2: moderate; 3: Severe). Based upon a Principal Component Analysis of the data from more than 1,100 MSQs, the SSQ extracted 16 symptoms out of 28, and weighted them into three major components: Nausea (e.g., general discomfort), Oculomotor problems (e.g., eyestrain), and Disorientation (e.g., vertigo). A total score can be obtained from the sub-scores calculated in these three components. With the SSQ, VIMS can be quantified for any systematic changes from pre-exposure to post-exposure. SSQ is used in this research. The advantage of using SSQ is that it links our findings to the international research community who are studying VIMS.

Another commonly-used subjective measurement of VIMS is the 7-point nausea rating scale proposed by Golding and Kerguelen (1992). The scale ranged from '0 – no symptom' to '3 – mild nausea' and to '6 – moderate nausea and want to stop'. Nausea is the most common and unique representative symptom across different types of motion sickness (e.g., car sickness, sea sickness), including VIMS. Comparing with the SSQ, the nausea scale may seem monotonic and less powerful. But its advantage over the SSQ is the capability to continuously measure levels of VIMS during the exposure of virtual environments because of its simplicity, thus producing the time course data that is useful in studying the generation and development of VIMS symptoms. This scale has been adopted by many studies (Woodman and Griffin, 1997; Holmes and Griffin, 2001; Lo and So, 2001; So *et al*., 2001b). In this study, the 7-point nausea is adopted. More recently, Keshavarz and Hecht (2011) applied a 21-point rating scale (from 0 – "no sickness at all" to 20 – "frank sickness") to assess VIMS during the presentation of stimuli. They claimed that their scale is better since it has a finer resolution (20 steps). But this could be its disadvantage because the scale is too long and the subjects could be easily confused about the specific meaning of each point on the 21-point rating scale and, in turn, increased the inter-subject variation and lower the reliability of the scale.

2.1.2.2 Objective Measurements

In addition to subjective measurements, objective measures have also been used to estimate the physiological representations of various symptoms of VIMS. These measurements include, but not limit to, postural instability, pallor of face, heart rate changes, skin conductance, etc. Among all, measuring the subjects' postural instability is the most popular method recorded in literature (Sugitaa and Yoshizawa et al., 2008; Cobb *et al*., 1999; Kennedy and Stanney, 1996; Kolasinski *et al*., 1994; Owen *et al*., 1998; Palmisano *et al*., 2011; Smart *et al*., 2002; Stoffregen *et al*., 2000; 2010; van Emmerik *et al*., 2011). In these studies, postural instability were represented by head or body sway, the center of pressure of a standing person on a force platform, or special stances (e.g., Sharpen Romberg Stance).

2.1.3 Susceptibility

About one-third of the Hong Kong Chinese are susceptible to (visually induced) motion sickness. Golding (1998) revised the motion sickness susceptibility questionnaire (MSSQ) originally proposed by Reason and Brand to include items concerning exposure and susceptibility to cinerama/video/simulator sickness. Reporting the susceptibility of the subjects has become a standard procedure in motion sickness studies to reflect a key characteristic of the chosen samples (Bos *et al*., 2010; Smart *et al*., 2002; Stoffregen *et al*., 2000). Studies on susceptibility to VIMS have showed that generally women are more susceptible than men (Flanagan *et al*., 2005). Lower postural instability and heart rate variability to moving visual stimuli are corresponding to a lower susceptibility to motion sickness (Yokota *et al*. 2005). In this study, MSSQ was used to measure the susceptibility to VIMS among our participants before the experiments.

2.1.4 Adaptation and Habituation

Repeated exposures to VIMS-provocative stimuli have been proved to reduce the severity of symptoms (Regan, 1995; Hill and Howarth, 2000; Kennedy *et al*., 2000). This reduction is dependent on the inter-exposure interval. Stern *et al*. (1989) reported that participants exposed to vection drum showed adaptation with inter-exposure intervals of 2 days, but did not do so when the interval was 4 days or longer. On the other hand, Regan and Price (1994) reported that repeated exposure to the same stimuli with separation of less than seven days could significantly reduce the levels of VIMS. In this study, we have kept, on average, 7 day separate between each exposure to VIMS provking stimuli in Experiments VIMS1 and VIMS2. However, we also acknowledge that there had been some except cases where the separation period was less than 7 days. In particular, since Expriments VIMS2 had 17 conditions, sometimes it was not possible to schedule all exposure to be 7 days apart due to subject availability.

2.2 Theories or Hypotheses on VIMS

2.2.1 The Sensory Conflict Theory

The sensory conflict theory proposed by Reason (1978) is the most widely accepted theory in explaining the occurrence of motion sickness. Its idea is simple: all situations that provoke motion sickness are classified as one situation in which sensory information from eyes and inner ears are not consistent about the motion. In particular, three types of sensory conflicts have been defined: (type I) when both visual and inertial stimuli are simultaneously in conflict; (type IIA) when only visual stimuli are present but at the absence of inertial stimuli; and (type IIB) when only inertial stimuli are present but at the absence of visual stimuli. According to this classification, VIMS should be cause by situations belonging to type IIA conflicts. In other words, the reason why stationary viewers who are exposed to provocative visual motion would suffer symptoms of VIMS is that a viewer constantly receive and update their locomotion information from the visual system and expect congruent information from the vestibular system that are missing. Therefore, the visual and vestibular signals are in contradictory position and this conflict eventually makes this viewer ill.

Although the sensory conflict theory has its ecological merit, it remains at a qualitative phase. The sensory conflict theory did not address the following questions. How can sensory conflict be measured? To what extent can sensory conflict be substantial enough to provoke symptoms of motion sickness? How is sensory conflict related to stimuli parameters (e.g., frequency, velocity, etc.)? Without answers to the above questions, the prediction of severity of VIMS remains impossible. One possible way to measure "conflict" is to shift the "conflict" from being a state of mind inside the brain to the measurements of visual cues and vestibular cues. In other words, for VIMS, focuses should be placed in quantifying the VIMS provoking visual stimuli.

2.2.2 The Spatial Velocity (SV) Hypothesis

The spatial velocity (SV) hypothesis is a step forward in quantifying the VIMS provoking visual stimuli. It focuses on relating the levels of VIMS with parameters of the VIMS provoking visual stimuli (So *et al*., 2001a). The basic idea is if the visual stimuli can be quantified by the unit SV, then the levels of VIMS may be related to an integration of SV over the duration of exposure. SV is a metric that quantified both the visual scene velocity and scene complexity (for detailed calculation of SV, please refer to So *et al*., 2001a).

Although the SV hypothesis does not directly address the frequency responses of VIMS, the fact that SV combines the visual scene velocity and scene complexity has placed the velocity of the visual stimuli at the center stage of quantifying VIMS provoking stimuli. The SV hypothesis suggests that, giving all things equal, exposure to two stimuli having the same scene complexity and same velocity should produce the same levels of VIMS. A review of literature shows that many studies on the frequency responses of VIMS have kept the velocity constant but varied oscillation amplitude to change the frequency of the stimuli. Consequently, according to this SV hypothesis, levels of VIMS should remain constant.

2.2.3 The Cross-over Frequency Hypothesis

Duh *et al.* (2004) proposed the cross-over frequency (COF) hypothesis. This hypothesis predicts that visual oscillations at 0.06 Hz should be the most sickness provocative stimuli. The basic idea behind the COF theory is that the frequency responses of human's sensitive to self-motion perception (real or illusive) as induced by visual motion and physical (i.e., vestibular) motion are different with the former reduces with increasing frequency and the latter increase with increasing frequency. Duh and his colleagues argued that at 0.06 Hz, the two frequency curves crossed over which implies that human are equally sensitive to visual oscillations and physical oscillations at 0.06 Hz. As such, if the visual oscillation and the physical oscillations are in "conflict", human would find it difficult to decide which stimuli to ignore and, hence, could not easily suppress the "conflict".

There have been some critics of the COF hypothesis. Bonnet *et al*. (2006) objected to the fact that Duh and his colleagues did not collect the frequency responses of self-motion perceptions in the same experiment. Bonnet argued that this is important as Duh used frequency curves collected in different settings to derive the COF. Also Diels and Howarth (2012) argued that the value of COF is subject to change if the tuning functions of visual and vestibular systems are not equally weighted. Notwithstanding all the criticism, the COF hypothesis is a good demonstration of the importance of studying the frequency responses of VIMS and self-motion perception.

2.3 Frequency Responses of VIMS

It has been suggested that frequency of oscillation of the visual scene may be an important factor affecting the generation of VIMS (Hettinger *et al*., 1990). The obvious extreme is, of course, 0Hz (without motion). There have been many past studies attempted to measure the effects of frequency of visual stimuli on levels of VIMS.

Duh *et al*. (2004) reported a significantly higher level of motion sickness in participants who were exposed to simultaneous visual and vestibular motions oscillating in yaw axis at slightly different frequencies around 0.06 Hz than at 0.2 Hz. Duh and his colleagues used this experiment to support their proposed COF hypothesis and then use the hypothesis to generalize their findings to motion sickness (including VIMS) in general. Duh's finding about the 0.06Hz sickness provoking stimulus was further supported by Lin *et al*. (2005) who reported that visual roll oscillations at 0.08 Hz presented in a driving simulator caused higher levels of VIMS than similar oscillations at 0.035 Hz and 0.213 Hz. Consistent findings were reported in a car simulator study in which the participants who were driving a car simulator inside a virtual test track with more lateral oscillations at 0.07 Hz reported more VIMS than driving at another test track with more lateral oscillations mainly at 0.46 Hz (Groen and Bos, 2008). All of the above studies reported evidences that levels of VIMS will be highest when exposed to visual oscillations at around 0.06 Hz along yaw; roll; and lateral axes. In particular, Duh *et al.* also generalize the 0.06 Hz findings to all types of motion sickness.

A review of literature also identified studies reporting different findings. In an experiment with participants exposed to yaw visual oscillations with 18º tilt at frequencies of 0.05 Hz, 0.2 Hz, and 0.8 Hz respectively, Golding *et al*. (2009) reported a significantly higher levels of VIMS at 0.2 Hz than other frequencies. Similarly, Diels and Howarth (2012) also reported a peak of VIMS severity when watching zooming random dot pattern at 0.2 Hz along the fore-and-aft axis as compared to similar stimuli zooming at the frequencies from 0.025 Hz to 1.6 Hz. Chen (2006) reported that levels of VIMS increased, peaked and reduced when watching visual oscillations along fore-and-aft, lateral, and yaw axes. Results indicated that when watching visual oscillations along fore-and-aft, lateral and yaw axis, levels of VIMS peaked at 0.375 Hz, 0.19 Hz and 0.19 Hz, respectively. Since Chen (2006) used the same virtual environments in her studies, she concluded that the general shape of frequency responses did not change among fore-and-aft, lateral and yaw axes. These three studies reported evidences that levels of VIMS will be highest when exposed to visual oscillations at around 0.2 to 0.38 Hz along yaw, lateral and fore-and-aft axes.

Since both clusters of studies involved visual motions in both rotational and translational axes, the argument that axis of motion is the key to explain the discrepancy could not be substantiated. This is also consistent with the findings reported in Chen (2006).

A further in-depth review of these studies suggests that with the exception of Golding *et al.* (2009) and Groen and Bos (2008), other studies could be grouped into two distinctive different groups: (i) studies in which the velocity of the visual oscillations were kept constant; and (ii) studies in which the amplitudes of the visual oscillations were kept constant. In the former studies, frequency was manipulated by changing oscillation amplitudes (i,e., effects of frequency was confounded with effects of amplitude) and in the latter studies, frequency was manipulated by changing oscillation velocities (i.e., effects of frequency was confounded with effects of velocity). In particular, Duh *et al*. (2004) and Diels and Howarth (2012) kept r.m.s. velocity constant and varied amplitudes; while Chen (2006) and Lin *et al*. (2005) kept the amplitude of visual oscillations the same and varied the r.m.s. velocities. Golding *et al*. (2009) did not specify which variable they used to manipulate frequency in their paper. Groen and Bos (2008) did not purposely manipulate frequency as conditions but rather they observed the main frequency components in the Power-Spectral-Density (PSD) of the visual stimuli along lateral axis, thus both velocity and amplitude were not fixed in their experiments. We acknowledge that this grouping of either keeping the stimuli's velocity or amplitude the same still could not explain the discrepancy in the findings. For examples, both Duh *et al.* (2004) and Diels and Howarth (2012) differed in their findings but both kept the velocity the same. Also, both Chen (2006) and Lin *et al.* (2005) kept the amplitude constant but differed in their findings.

In summary, frequency response of VIMS has been the subject of many studies but the results have not been consistent. A review of literature indicate that three factors that could be contributing to the discrepancy between the findings: (i) axis of visual motion; (ii) methods of manipulating the frequency (i.e., manipulating velocity while keeping the amplitude the same or manipulating amplitude while keeping the velocity the same); and (iii) scene complexity. Since Chen (2006) has studied the effects of axis of motion while controlling the scene complexity to be the same by using the same virtual environment, in this thesis I focus on how the method of manipulating frequency would have affected the shape of the frequency responses of VIMS, vection and perceived speeds with two different levels of scene complexity. Using the SV hypothesis proposed in So *et al*. (2001a), this thesis hypothesizes that when the stimuli's velocities are kept constant, the levels of VIMS should be similar across different frequencies and when the stimuli's amplitudes are kept constant, the levels of VIMS should increase, peak and reduce or to the least significantly vary with increasing frequency (see Chapter One for more details on the two-frequency-response hypothesis. A review of literature indicates that, there has been no published study to verify this two-frequency-response hypothesis.

2.4 Summary

Strong effects of frequency on VIMS have been identified in previous studies but had been confounded with effects of velocity or amplitude. Studies to determine how such confounding effects will affect the shape of the frequency responses of VIMS could not be found. Aiming at filling up such an important research gap, the following chapters describe a series of experiments to study and isolate the effects of velocity and amplitude on frequency responses of VIMS with two levels of scene complexity.

CHAPTER 3: METHODS AND APPARATUS

SUMMARY

This chapter summarizes methods and apparatus used in this study. In particular, the experimental setups including the laboratory apparatus and the stimuli presented in Experiments PS1, PS2, VIMS1 and VIMS2 are introduced, followed by descriptions of different dependent measures (e.g., nausea ratings, vection ratings, postural sway). By reporting the detailed experimental setup here, the author would like to focus more on the research rationale and the data analyses in Chapters 4 and 5. All four experiments reported in this thesis were approved by the human subject committee at the Hong Kong University of Science and Technology. Written consent were obtained from all the participants.

3.1 Experimental Setups and Stimuli

While all four experiments were conducted in the same laboratory, Experiments PS1 and VIMS1 shared the same visual stimuli while Experiments PS2 and VIMS2 shared another set of visual stimuli. A set of zooming virtual tunnel stimuli were used for PS1 and VIMS1 (Figure 3.1) and a zooming random dots stimuli were used in PS2 and VIMS2 (Figure 3.2). All zooming visual motions were along the fore-and-aft direction of the viewers. The virtual tunnel stimuli appeared as a zooming radial checker-board pattern. These stimuli were constructed from a series of pictures captured from a specifically constructed 3D tunnel model using the 3D Studio Max™ software. The viewpoints of the stimuli were pre-programmed to move according to some pre-determined paths. This allowed the velocity and amplitude of each visual motion stimulus to be determined in a very precise way. Also, using captured views of a 3D virtual tunnel created in 3D Studio instead of just drawing them using a program gave the stimuli more physical meanings. For example, I can say that all virtual tunnel stimuli were perspective views captured by a virtual camera inside a computer-aided designed model of a tunnel. By sharing the 3D Studio file, other researchers can easily reconstruct the stimuli that I have used.

The random dot stimuli were constructed using the COGENT^{TM} software running in the Matlab software environment. The reason of using COGENT^{TM} was to be as consistent as possible to Diels and Howarth (2012).

3.1.1 Setup 1 and the virtual tunnel stimuli

For Experiments PS1 and Experiment VIMS1, participants were requested to stand in front of a wide field-of-view (FOV) cylindrically installed (diameter: 2.2 metre) white projection screen (DaMatt, Da-Lite Screen Company, Inc., Indiana. Neutral gain: 1.0; dimensions: width 4.6 x height 2.0 metre). Three NEC LT-380 LCD projectors (NEC, Corp., USA) simultaneously projected images side-by-side onto the projection screen. The three projected images covered a FOV of 200º (horizontal) x 50º (vertical) when the viewing distance was 1.1 metre. Edge blending was applied to smooth out the overlapping areas between projections of adjacent projectors. As explained above, visual stimulus was created and rendered using 3D Studio Max^{TM} 6.0 as sequences of high-resolution slides that were played back at 60 frames per second with a Microsoft DirectDraw graphics programme running on a Pentium Core2Duo PC computer with an NVidia GeForce 7600 GT graphics card (NVidia Corporation, USA). The visual stimulus images were sent to a Triplehead2Go module (Matrox Electronic Systems, USA), which split the image into three 640 x 480 pixel VGA signals to be displayed by the three LCD projectors at 60 Hz refresh rate.

The visual stimulus was a perspective view from a virtual camera moving inside a long circular tunnel with radial black-and-white checkerboard patterned interior (5 metre radius, 2,000 metres in length inside 3D Studio). Similar to Duh *et al.* (2004)'s experiment, eight pairs of radial black-and-white stripes were used (see Figure 3.1). This stimulus has two advantages: (i) it combines the characters of the stimuli of the two previous studies: radial star-field in Diels and Howarth (2012) and striped patterns in Dul *et al.* (2004); and (ii) the scene was constructed in a 3D CAD model with known relative dimensions for ease of reconstruction. Along the length of the tunnel, there were 50 pairs of black-and-white ring patterns evenly distributed along the 2,000 metre tunnel. Luminance of the projected white stripe on the screen was measured as 130 cd / m^2, and the luminance of the projected black stripe on the screen was 18 cd / m^2, as measured by a Minolta Chroma Meter CS-100 (Minolta Co. Ltd., Japan). The tunnel oscillated back-and-forth, zooming in and out along the fore-and-aft axis. With normal blinks allowed, the participants were asked to fixate their gazes at the centre of the image (a black dot subtended at an angle of 1.04°). The centre of the virtual tunnel was aligned with the eye levels of the participants). In addition, a camera was placed around 1 metre away on the right side of the participants, sending real-time images to a PC behind the screen for the experimenter to monitor the participants' behaviors. In Experiments PS1 and VIMS1, conditions were grouped by their levels of r.m.s. velocities: 11.1, 22.2, 44.4, 88.9, 177.9 m/s. To help readers to visualize what the participants would have seen (Figure 3.1), it might be helpful to illustrate the velocity by counting how many black-and-white pair of radial stripes that they passed through 'virtually or visually' in one second. As stated above, the 2000 meter long tunnel had 50 pairs of black-and-white circular stripes along its length and each pair of black-and-white stripes spanned 40 meters along the length of the tunnel. Consequently, at a condition in which the participants were travelling 'virtually' down the tunnel at 44.4 m/s, they would have passed through one pair of black-and-white stripes in one second.

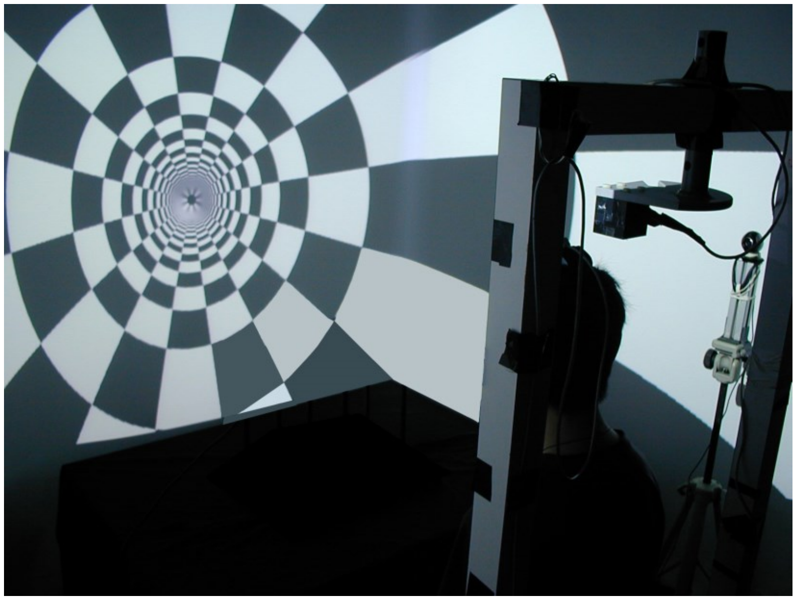


Figure 3.1 The expermental setup (Setup 1) and the virtual tunnel stimuli used for Experiments PS1 and VIMS1.

3.1.2 Setup 2 and the random dots stimuli

The motivation of Experiments PS2 and VIMS2 was to examine whether the findings reported in Experiments PS1 and VIMS1 would still hold when the stimuli changed to those similar to be Diels and Howarth (2012). Findings of Experiments PS1 and VIMS1 contradicted those of Diels and Howarth (2012) (Chapter 4). Therefore, Setup 1 had been modified to be Setup 2 (see Figure 3.2) to be as consistent to Diels and Howarth (2012) as possible. In Setup 2, participants were required to sit on a chair fixed to the ground with its height adjustable in front of the same table as in Setup1 (see Figures 3.1). Diels and Howarth (2012) used seated subjects. Regan (1993) found that standing and sitting posture did not affect the reported levels of VIMS but seated participants were still used so that Experiments PS2 and VIMS2 were closer to Diels and Howarth (2012)'s study. Participants' head movements were limited by a chinrest stand fixed at the edge of the table. Each participant wore a custom-made goggle that restricted their visual field to approximately 60º x 50º and occluded any visual references (the floor, screen edges, etc.). During the experiment, the visual stimulus was the only images that the participants saw.

The visual stimuli were similar to that used in Diels and Howarth (2012). It consisted of a random dots pattern with 500 moving white filled-in circles (100 cd / m^2) on a black background (1.07 cd / m^2). The stimuli were produced using the COGENT™ Graphics Toolbox embedded in Matlab (version 6) installed in the same PC mentioned in the Setup 1. Only the central projector was used for stimuli projection and a resolution of 1280x1024 pixels. Similar to Diels and Howarth (2012), the movements of the dots on the display were programmed to geometrically map to perspective motion along the fore-and-aft axis (i.e., the velocity and size of each dot varied exponentially as a function of its simulated location in depth, according to Andersen and Braunstein, 1985). The expansion and contraction of the dots created a zooming star field view along the fore-and-aft axis of the viewers. A red dot subtended a visual angle of 0.5° was displayed at the centre of the display as an eye-fixation pointer. Participants were instructed to fixate at the red dots while the dots were moving (again, normal blinks were allowed). A keyboard was placed on the table at the side of a participant's dominant hand (i.e., the keyboard was placed at the left side of the table if the participant was left hand dominant and vice versa). Similar to Setup 1, a camera was also placed aside of the participants to monitor their head motions.

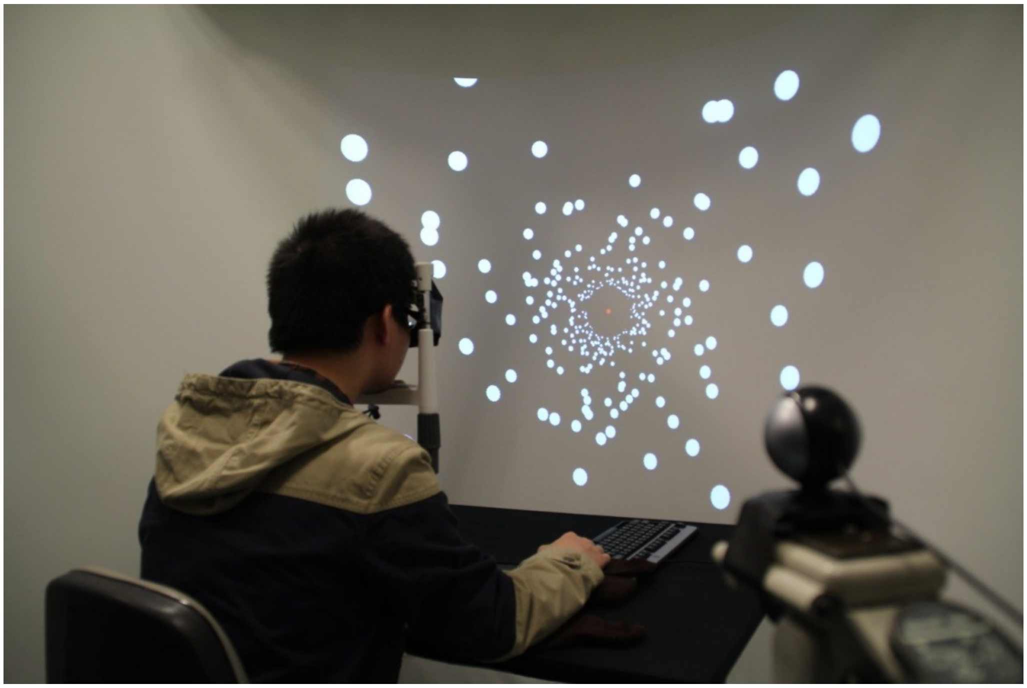


Figure 3.2 The experimental setup (Setup 2) and the random dots stimuli used for Experiments PS2 and VIMS2.

3.2 Measurements and Dependent Variables

3.2.1 Nausea ratings

During exposure of visual motion, participants were asked to self-report their sickness severity according to a 7-point nausea rating scale at 5-min intervals. The 7-point nausea rating scale is a Likert scale adopted from Golding and Kerguelen (1992) (see Table 3.1).

Table 3.1 Nausea Rating Scale

	Nausea Rating Scale (adapted from Golding & Kerguelen, 1992)
0	No symptom
1	Any unpleasant symptom, however slight
2	Mild unpleasant symptoms, e.g. stomach awareness, sweating but no nausea
3	Mild nausea
4	Mild to moderate nausea
5	Moderate nausea but can continue
6	Moderate nausea, and want to stop

The exposure would be stopped when a nausea rating of 6 ('moderate nausea and want to stop') was reached, or the full 30-min duration of exposure had been completed, whichever was the sooner. The maximum value of 6 was assigned to the remaining nausea ratings for participants who reached a nausea rating of 6 before the end of the exposure (i.e., 30 min). For the purposes of data analyses, the nausea ratings reported at 30 min of exposure, the accumulative nausea ratings over the 30 min period, the time taken to reach each level of nausea ratings, and the proportion of participants that reached each level of nausea ratings were extracted.

3.2.2 Motion sickness susceptibility questionnaires Short-form (MSSQ-short)

After a participant was recruited, he or she was asked to complete a short form of the motion sickness susceptibility questionnaires (MSSQ; Golding, 1998). The MSSQ is a survey to quantify people's susceptibility to nauseogenic conditions by setting a series of questions of each individual's past history of motion sickness. The layout and the scoring method of the MSSQ are attached in Appendix 3.1. It has two sections. Section A concerned with one's experiences of travel and motion sickness as a child before the age of 12. Section B concerned with the experiences of travel and motion sickness in the past 10 years. The raw score of the MSSQ is a simple addition of the scores from both sections (MSSQ = MSA + MSB). The MSSQ raw score is then converted to the percentile score of MSSQ, with the 50%-tile representing the susceptibility of a normal population.

3.2.3 Simulator sickness questionnaires (SSQ)

Before and after the exposure of visual motion, participants were asked to self-report a list of 26 symptoms related to VIMS using the simulator sickness questionnaires (SSQ; Kennedy *et al*., 1993). The names of symptoms are summarized in Table 3.2 (with Chinese translations).

Table 3.2 Symptoms listed in the Simulator Sickness Questionnaires (SSQ)

1. General discomfort	一般不適	10. Nausea	作 嘔	19. Aware of breathing	呼 吸 異 樣
2. Fatigue	疲 倦	11. Difficulty	很難集中精神	20. Stomach awareness	胃感覺異樣
3. Boredom	沉 悶	12. Mental depression	精神的壓抑	21. Loss of appetite	沒 有 胃 口
4. Drowsiness	想 睡	13. "Fullness of the head"	頭 脹	22. Increased appetite	胃 口 增 加
5. Headache	頭 痛	14. Blurred vision	視野模糊	23. Desire to move bowels	想去洗手間
6. Eyestrain	眼 痛	15. Dizziness eyes open	眼 花 (開)	24. Confusion	迷 惘
7. Difficulty focusing	很難集中視力	Dizziness eyes close	眼 花 (合)	25. Burping	打 嗝
8. Salivation increase	口水分秘增加	16. Vertigo	眩 暈	26. Vomiting	嘔 吐
Salivation decrease	口水分秘減少	17. Visual flashbacks	幻 覺	27. Other	其 他
9. Sweating	出 汗	18. Faintness	昏 厥		

The SSQ symptoms were rated using a 4-point Likert scale (0-none; 1-slight; 2-moderate; 3-severe). According to results of factor analyses reported in Kennedy *et al.* (1993), only selected critical symptoms were contributed to the computation of the SSQ scores. Besides the total SSQ scores, three sub-scores of the SSQ were also computed: nausea score, oculomotor score, and disorientation score. The selected symptoms and their weightings to each of the sub-scores and the total score are listed in Table 3.3. Each score is obtained by summing up the product of the severity score and the corresponding weighting for every symptom, and then multiplying by a scaling value (3.74 for total score (T), 9.54 for nausea (N), 7.58 for oculomotor (O), and 13.92 for disorientation (D)).

Table 3.3 Weightings of selected symptoms to SSQ sub-scores: Nausea (N), Oculomotor (O), Disorientation (D), and Total scores (T).

	Weight			
SSQ Symptom	N	O	D	T
General discomfort	1	1		2
Fatigue		1		1
Headache		1		1
Eyestrain		1		1
Difficulty focusing		1	1	2
Increased salivation	1			1
Sweating	1			1
Nausea	1		1	2
Difficulty concentrating	1	1		2
Fullness of head			1	1
Blurred vision		1	1	2
Dizzy (eyes open)			1	1
Dizzy (eyes closed)			1	1
Vertigo			1	1
Stomach awareness	1			1
Burping	1			1

The SSQ that used before the start of an exposure is named as "Pre-SSQ" while the SSQ that used after the end of an exposure is named as "Post-SSQ" (see Appendix 3.2). For those participants who reported a pre-SSQ total score more than 7.48, they were asked to take a rest of at least 5 min and then performed the pre-SSQ again. If they still report a pre-SSQ total score of greater than 7.48, a different date of the experiment was scheduled (Stanney *et al.*, 2002). This practice eliminated those participants who might have suffered from some sickness symptoms before the exposure. For the purpose of data analyses, the difference between the post-SSQ score and the pre-SSQ score were calculated to indicate the increases in SSQ score due to the 30-min exposure. The proportion of participants who had an increase of SSQ scores (post - pre) were also calculated.

3.2.4 Perceived speed and how it was measured

In Experiments PS1 and PS2, participants were asked to compare and rate the subjective perceived speed of each visual oscillation against a reference oscillation using a ratio-scale method. Since all oscillations were sinusoidal, the speed varied (i.e., fastest at the mid-point and come to a stop at the far-end of a sine wave). However, participants were asked to subjectively judge and compare the average perceived speed of oscillation between the reference oscillation and the stimulus oscillation. A special training session was given to the participants so that they would not confuse perceived speeds with perceived frequencies because different oscillating amplitudes were used. The definition of perceived speed was "how fast you felt the patterns were travelling relative to you" while the definition of frequency was "the number of cycles of oscillations completed by the moving patterns per unit time". Participants were educated to understand that the two variables were not the same depending on the amplitudes of oscillations.

For each pair of comparison, participants were first presented with a reference oscillation for 20s. The average speed of the reference oscillation was assigned as 100 units per second. Immediately after the reference oscillation, the signal oscillation was presented for as long as the participants needed to report the perceived average speed of this oscillation. For example, if the signal oscillation was perceived at a same averaged speed with the reference oscillation, the participants reported 100. If the signal oscillation was perceived as 50% slower, the participants reported 50. If the signal oscillation was perceived to be twice as fast, the participants reported 200. The participants were free to report any integer number like 70, 25, 39, 120… etc. During each presentation, the participants were asked to fixate their eyes on the center of the visual oscillating pattern (normal blinks were allowed).

Since the perceived speed task involved skills of ratio scaling, all participants had to be trained and passed a line-length estimation test with an R-square larger than 0.9 before they could proceed to the experiments (Parker *et al.*, 1975). In this test, a participant was required to compare lines with different lengths relative to a reference line. The signal lines could be longer or shorter than the reference line. R-square of the line-length estimation test was calculated by fitting a line in a plot of the evaluated line lengths against the true line lengths.

3.2.5 Vection Measurements

Together with nausea ratings, participants were also asked to self-report the intensity of their illusive sensation of self-motion (vection) according to the vection ratings scale at 5-min intervals during exposure of visual motion. The vection ratings scale is a 7-point Likert scale from 0 - 6 modified from Webb (2000) shown in Table 3.4.

Table 3.4 Vection Rating Scale

	Vection Rating Scale (adapted from Webb, 2000)
0	I perceive that the only thing moving is the visual stimulus and I remain stationary (No Vection)
2	I perceive that visual stimulus to be moving but also experience weak feeling of self-motion (Weak Vection)
4	I perceive that visual stimulus to be moving but also experience strong feeling of self-motion (Strong Vection)
6	I perceive that the visual stimulus is stationary, and a strong feeling that I am moving (Strong and Total Vection)

The vection ratings scale ranges 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"), reflecting the relative intensity of perceived motion between the participants themselves and the visual stimuli. All participants were educated about the meaning of vection before the experiment to make sure that they understood the difference between illusive self-motion and stimuli motion. The classical train scenario was used: imagine when you were sitting aside a window on a train in a train station waiting to set off; the view of the window is blocked by another train next to yours; when the neighboring train started to move, for a few seconds, you had a strong feeling, perceived and believed that you were moving away from the neighboring train and the station (assuming that neighboring train was stationary) even though you were in fact stationary. Participants were educated to anchor that moment of sensation as level '6' on the vection scale. It was interesting to note that all participants had experienced that situation at least once in their life time either on a train or on a plane or other vehicles waiting to set off. For the purpose of data anaoyses, particular interest was given to the measures of vection ratings at 30 min and the average vection ratings across the entire 30 min period.

In addition to the vection ratings, the duration of experiencing vection sensation (however small) during exposure to visual stimuli was evaluated by pressing two keys (forward and backward keys: indicating the direction of vection feeling) on a keyboard by pre-positing their fingers on the appropriate keys so that they could press them without moving their gazes away from the stimuli. Participants were instructed to press the forward key if they perceived forward self-motion and press the backward key if they perceived backward self-motion. When they were not experiencing vection, the keys were released. The signal from the keyboard was stored for later analysis.

3.2.6 Postural Measures

Postural sway data were collected using a Polhemus 3-Space Fastrack system (Polhemus Inc., USA) with an electromagnetic receiver placed at the crown of each participant's head (fixed onto an acoustic headset worn by the participants, see Figure 3.3).

Figure 3.3 Measurement of postural sway using the Polhemus 3-Space Fastrack system (Polhemus Inc., USA).

An electromagnetic transmitter was positioned approximately 5 cm above the receiver on top of the participants while they viewed the visual stimulus in an upright standing posture. The position data of the receiver were captured real-time in a six-degree-of-freedom coordinate system (x, y, z, azimuth, elevation, and roll) with a sampling rate of 30 Hz and spatial resolution of 0.0005 cm.

The postural sway data series over the 30-min exposure were processed off-line in the following procedures. Firstly, the time-series data were detrended. Secondly, the root-mean-square (r.m.s.) values of the three translational axes (x, y, z) were calculated for every time point to form a time series of r.m.s. postural sways. Lastly, the inter-quartile range (IQR) of the r.m.s. time series were calculated to represent the postural sways of a participant over an experimental condition.

3.2.7 Visual acuity

All participants were tested for visual acuity using an Optec2000 Vision Tester (Stereo Optical Corp.) before the experiments. Only those who had a normal or correct-to-normal (i.e., with glasses) vision acuity were recruited. The visual acuity was measured using a Snellen scale, which defines a normal visual acuity as 20/20 (at a distance of 20 feet, a human eye with nominal performance is able to read a line that subtends a visual angle of one minute of arc). The numerator of the Snellen fraction (e.g., 20/20) was the distance in feet the participant is from the eye chart. The denominator represented the distance a "normal" human eye can read the same line. Therefore, a vision of 20/10 corresponded to a better than "normal" vision acuity and a vision of 20/40 corresponded to a worse level of visual acuity. The instruction and the test chart are shown in Appendix 3.3.

Figure 3.4 Measurement of visual acuity using Optec2000 Vision Tester (Stereo Optical Corp.).

3.3 Data analysis

Non-parametric statistical methods were used throughout due to the non-Gausian nature of the experimental data collected in this thesis. More specifically, non-parametric statistics for dependent samples were used throughout since all experiments adopted a within-subject design. Tests used included: Friedman repeated measures analysis of variance by ranks; Wilcoxon matched-pairs signed ranks tests; and Spearman rank-order correlation tests. For dichotomous data, the Cochran Q test was used to find difference between more than two conditions and the McNemar's change test was used to compare the difference between two conditions. The data were analyzed using the software package IBM SPSS Statistics 21.

CHAPTER 4: FREQUENCY RESPONSES OF PERCEIVED SPEED (PS) AND VECTION WHEN VIEWING STIMULI OSCILLATING ALONG FORE-AND-AFT AXIS: KEEPING R.M.S. VELOCITY CONSTANT V.S. KEEPING AMPLITUDE CONSTANT

SUMMARY

This chapter describes two experiments that studied perceived speed (PS) and perceived vection to examine the two-frequency-response hypothesis (see Chapter one). In the first experiment (Experiment PS1), ten participants (4 females and 6 males, aged between 20 to 23 years old) were exposed to radial checker-board pattern oscillating in the fore-and-aft axis. Effects of different combinations of nine r.m.s. velocities (from 2.78 m/s to 710.86 m/s), nine amplitudes (from 3.125 m to 800 m), and nine frequencies (from 0.0125 Hz to 3.2 Hz) were studied. The second experiment (Experiment PS2) was similar to Experiment PS1 but participants were exposed to a radially scattered random-dot pattern oscillating also along the fore-and-aft axis. Fifteen participants (7 males and 8 females) with an average age of 20.3 (±3.2) years old took part in Experiment PS2. Results from both experiments consistently confirmed the two-frequency-response hypothesis for perceived speed and perceived vection when participants were watching visual stimuli oscillating in the fore-and-aft axis. Influences of velocity, amplitude, and frequency on perceived vection and perceived speed are discussed.

4.1 Introduction

4.1.1 Importance of studying frequency responses

Effects of motion (both visual and physical) frequency on motion perception, induced self-motion, and other physiological and psychological effects have been the subjects of many behavioral and / or physiological studies (Babler and Ebenholtz, 1989; Chen *et al.*, 2012; Chen-Huang and Peterson, 2010; Chow *et al.*, 2007; Diels and Howarth, 2006, 2012; Dijkstra *et al.*, 1994; Donohew and Griffin, 2004; Duh *et al.* 2004; Griffin and Mills, 2002; Golding *et al.*, 1996, 1997, 2001; Hlavacka *et al.*, 1996; Howarth and Griffin, 2003; Kawakami *et al.*, 1998; Kawakita *et al.*, 2000; McCauley *et al.,* 1976; O'Hanlon and McCauley, 1974; Previc *et al.*, 1993; van Asten *et al.*, 1998; Wood, 2002; Yakusheva *et al.,* 2008).

4.1.2 Two methods of manipulating frequencies and the implications

A review of the above mentioned studies indicate that they can mainly be divided into two groups according to the methods used to manipulate the frequency. Studies in the first group manipulated the frequency of motion (visual or physical) by changing the amplitude but keeping the root-mean-square (r.m.s.) velocity, or peak velocity constant (e.g. Chen *et al.*, 2012; Chen-Huang and Peterson, 2010; Chow *et al.*, 2007; Diels and Howarth, 2006, 2012; Dijkstra *et al.*, 1994; Donohew and Griffin, 2004; Duh *et al.* 2004; Griffin and Mills, 2002; Kawakita *et al.*, 2000) or keeping the r.m.s. acceleration constant (e.g. Golding and Markey, 1996; Golding *et al.*, 1997, 2001; Kawakami *et al.*, 1998). Studies in the second group manipulated the frequency by changing levels of r.m.s. velocity or r.m.s. acceleration of the stimulating motion but keeping amplitude constant (Babler and Ebenholtz, 1989; Hlavacka *et al.*, 1996; Howarth and Griffin, 2003; Previc *et al.*, 1993; van Asten *et al.*, 1998; Wood, 2002).

However, all of the above research referred to their findings as frequency responses and there was no formal or explicit attempt to label the two types of frequency responses (i.e., one obtained with stimuli of constant r.m.s. velocities or accelerations, and the other obtained with stimuli of constant amplitudes). This could cause unnecessary confusion if the two types of frequency responses are different. In this thesis, our attention is on the lack of specific study focusing on these two types of frequency responses with visually induced motion sickness (VIMS).

4.1.3 Research gaps and motivations

As reported above, the focus of our present research is on visually induced motion sickness (VIMS). With VIMS, the two types of frequency responses had not been reported from a single study using the same sets of stimuli. Therefore, the differences between the two types of frequency had been hypothetical. Although comparisons using literature indicated that the two frequency responses might be different, results are complicated with confounding influences. Hence, a research gap has been identified.

Aiming to fulfill such the research gap, two experiments studying vection and perceived speed when viewing two types of visual stimuli oscillating sinusoidally along fore-and-aft axis with different frequencies manipulated by both keeping the r.m.s. velocity constant and keeping the oscillating amplitude constant. In these two experiments, vection and perceived speed were studied instead of VIMS for the following reasons: First of all, perceived speed (PS) are simple and direct measurements closely linked to VIMS. Reisbeck and Gegenfurtner (1999) found that the visual motion processing mechanism of human observers showed a velocity-tuned property, which means perceived speed has a direct link to the perceived mechanism of visual motion. Secondly, frequency responses of vection had been used to predict the frequency responses of VIMS. Vection, or the illusive perception of self-motion, has been found to be highly correlated with motion sickness (Hettinger *et al*., 1990; Flanagan *et al*., 2004; Palmisano *et al*., 2007). The term "Vection-induced motion sickness" was invented based on the apparent correlation between vection and motion sickness (Hu *et al*., 1997). As a result, vection has been used to predict the provocation of VIMS (Duh *et al*., 2004). Last but not least, there was a practical reason for choosing vection and perceived speed instead of motion sickness. To explore the two methods of frequency manipulations, a relatively large combination of experiment conditions were needed. If VIMS is measured, each trial would require at least 30 minutes exposure to the visual stimuli. For a within-subject design, this would pose a real challenge as each exposure would need to be separated by at least 4 days. For examples, if there were 37 conditions, each subject would take at least 4x37 days (5 months) to complete all exposure let alone there would be other complications such as subject unavailability. On the contrary, if only vection and perceived speed were measured, all measurements could be done in seconds and there were no adaptation effects due to the relatively short exposure time as well as the reflex nature of the measurements. In summary, vection and perceived speed were chosen as the measurements in these two experiments (Experiments PS1 and PS2) so that more combinations of conditions could be studied.

Measurements of VIMS would be done in the next two experiments (Experiments VIMS1 and VIMS2).

Unlike studies with motion sickness caused by physical motion, velocity instead of acceleration was used as one of the manipulating factors in the current experiments. The decision was made based upon the findings that a person's visual sensitivity prefers velocity rather than acceleration (Schrater *et al*., 2000; and Schaffer and Durgin, 2010). In summary, these two experiments would focus on the effects of three independent variables: velocity and amplitude of the stimuli whose combination was used to manipulate the frequency of the visual motion.

4.1.4 Objectives of Experiments PS1 and PS2

There are three objectives to be achieved by Experiments PS1 and PS2: (1) to study two types of frequency responses of vection and perceived speed; (2) to validate two-frequency-response hypothesis with different stimuli; and (3) to compare effects of stimuli velocity, frequency, and amplitude on vection and perceived speed. To achieve objective (1), Experiment PS1 was conducted to test the hypothesis that frequency responses of vection and perceived speed for viewing oscillating scenes would be different if the frequencies of stimuli are manipulated differently either by (i) changing amplitudes but keeping r.m.s. velocities constant; or (ii) varying r.m.s. velocities but keeping amplitudes the same. To achieve objective (2), a second experiment (Experiment PS2) was conducted to test the two-frequency-response hypothesis using a different visual stimulus. More specifically, the stimuli used in Experiment PS2 were adopted from Diels and Howarth (2012) – one of the studies that were closest to my research.

4.2 Hypotheses

It was hypothesized that manipulating the stimuli's frequencies by changing the amplitude of oscillation or changing the velocity of the oscillation would result in different frequency responses. This hypothesis has been named as "the two-frequency-response hypothesis" in Chapter one.

4.3 Methods

4.3.1 Experiment PS1

Participants

Ten university students (4 female and 6 male) aged between 20 to 23 years participated in the experiment. All of them were recruited by advertising on the student community website of the Hong Kong University of Science and Technology. None of them had participated in a similar study before. All participants passed the line length estimation test with R-square greater than 0.9 before the start of the experiments so as to ensure their ability giving ratio scaling data (see Chapter 3 for details of the test). All the participants had normal or correct-to-normal visual acuity. They all signed a consent form voluntarily before the start of the experiment.

Apparatus and Stimulus

The stimulus and apparatus of this experiment have been described in Chapter 3 as Setup 1 with the virtual tunnel stimuli.

Experimental Design

Experiment PS1 had three independent variables: (i) amplitude of visual motion oscillations with five to nine levels; (ii) velocity of visual motion oscillation with five to nine levels; and (iii) repetition with four levels. As explained before (see Chapter one), combinations of velocity and amplitude form a many-to-one relationship with the frequency of the visual oscillations. More specifically, when amplitudes were held constant, each level of velocity produced a unique level of frequency and when velocity was held constant, each level of amplitude produced a unique level of frequency. In this experiment, r.m.s. velocity was held constant at 5 levels: 11.1, 22.2, 44.4, 88.9 and 177.8 m/s and at each level of constant velocity, stimuli with 5 to 7 levels of amplitudes were used to produce visual oscillations with 5 to 7 frequencies ranging from 0.025 Hz to 3.2 Hz. Similarly, amplitude was held constant at 5 levels: 12.5, 25, 50, 100 and 200 meters and at each level of constant amplitude, stimuli with 5 to 7 levels of r.m.s. velocity were used to produce visual oscillations with 5 to 7 frequencies ranging from 0.025Hz to 3,2 Hz. The combinations of velocity and amplitude used in this experiment are shown in Figure 4.1. There were 37 conditions. As illustrated in the figure, the experiment aimed to test at least five frequencies (0.05, 0.1, 0.2, 0.4 and 0.8 Hz) at five constant r.m.s. velocities and at five constant amplitudes. More than 25 conditions were needed so as to achieve the desire range of frequency (see Figure 4.1).

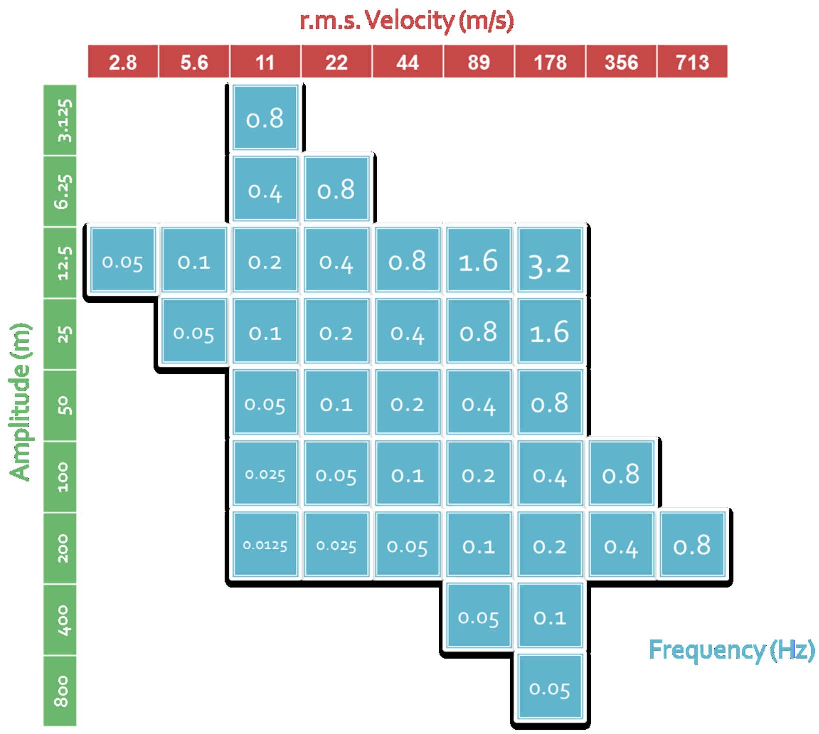


Figure 4.1 An illustration of the 37 conditions of Experiments PS1.

The experiment measured two main dependent variables: (i) rated r.m.s. perceived speed and (ii) rated perceived vection. The experiment used a reference-based ratio scaling method and the reference stimulus was chosen to have a r.m.s. velocity 44.43 m/s (peak velocity around 63 m/s) at 0.2 Hz with an amplitude of 50 meters. As illustrated in Figure 4.1, 44.4 m/s was at the middle of the range of velocities whose effects were investigated. Details on the procedure of measuring the ratio scaling data are explained in the next section. Table 4.1 summarizes the velocity, amplitude, and frequency of all 37 conditions.

Table 4.1 DOE of Experiment PS1

Cond #	Freq (Hz)	RMS Vel (m/s)	Amp (m)	Cond #	Freq (Hz)	RMS Vel (m/s)	Amp (m)	Cond #	Freq (Hz)	RMS Vel (m/s)	Amp (m)
1	0.8	11.1	3.125	14	0.4	44.4	25	27	0.8	355.4	100
2	0.4	11.1	6.25	15	0.8	88.9	25	28	0.0125	11.1	200
3	0.8	22.2	6.25	16	1.6	177.7	25	29	0.025	22.2	200
4	0.05	2.8	12.5	17	0.05	11.1	50	30	0.05	44.4	200
5	0.1	5.6	12.5	18	0.1	22.2	50	31	0.1	88.9	200
6	0.2	11.1	12.5	19	0.2	44.4	50	32	0.2	177.7	200
7	0.4	22.2	12.5	20	0.4	88.9	50	33	0.4	355.4	200
8	0.8	44.4	12.5	21	0.8	177.7	50	34	0.8	710.9	200
9	1.6	88.9	12.5	22	0.025	11.1	100	35	0.05	88.9	400
10	3.2	177.7	12.5	23	0.05	22.2	100	36	0.1	177.7	400
11	0.05	5.6	25	24	0.1	44.4	100	37	0.05	177.7	800
12	0.1	11.1	25	25	0.2	88.9	100				
13	0.2	22.2	25	26	0.4	177.7	100				

Procedures and Measurements

In this experiment, participants were asked to compare the average apparent velocities of the visual oscillating patterns between a reference oscillation and a signal oscillation. For each pair of comparisons, a reference oscillation was presented first for 20s followed immediately by the signal oscillation. The signal oscillation was shown until the participants were able to report the ratio scaling perceived speed of the signal relative to the reference stimulus. In order to simplify the task, nine choices of ratios (from 16 times; 8 times; …; to 1/8 times; and 1/16 times) were provided and the participants were required to choose one out of the nine ratios closest to their perception. Participants were educated about the nine choices before the experiment using the line length estimation test. The intensity of vection was measured using a 4-point Likert scale: 0 – 3 corresponding to none, slight, medium, and strong vection, respectively.

The 37 conditions were grouped into three sessions and each session lasted about 8.5 (±1.7) minutes on average. The SD was due to differences in the time taken to report the various ratings. The presentation orders of the sessions and the conditions within each session were both randomized. Participants were asked to fill in the Simulator Sickness Questionnaires (SSQ) after each session to check whether they were suffering from any sickness symptoms. All participants were asked to take a 5-minute rest and completed the SSQ again. If the score of SSQ was zero, participants would proceed to the next session; if not, they would take a rest for another 5 minutes and completed another set of SSQ. All participants completed their three sessions on the same day and all participants repeated the three sessions four times on separate day.

4.3.2 Experiment PS2

This experiment was identical to Experiment PS1 except for the following changes.

Participants:

Fifteen university students (8 female and 7 male) with average age of 20.3 (SD±3.2) years participated in the experiment. None of the participants took part in Experiment PS1. They were all fresh recruits.

Apparatus and Stimulus:

The stimulus and apparatus of this experiment are described in Chapter three as Setup 2 with the random dots stimuli.

Experimental Design:

The main objective of this experiment was to validate the two-frequency-response hypothesis, proven in Experiment PS1, with a different stimulus because the findings of Experiment PS1 contradict the findings in Diels and Howarth (2012). In this experiment, the stimuli used in Diels and Howarth (2012) was adopted. Being the second experiment, the scope of the experiment was narrowed to the effects of visual oscillations with five frequencies when velocity was held constant at 22.2 m/s and when amplitude was held constant at 25 meters. As illustrated in Figure 4.2, this was accomplished with 9 conditions and 4 more conditions were added to monitor whether the results in this experiment was consistent with the findings of Experiment PS1. The amplitudes, velocities and frequencies of the stimuli used in the 13 conditions are summarized in Table 4.2. The experiment used a within-subject design and all participants took part in all 13 conditions. The average duration for the 13 conditions was about 10.5 (±2.2) minutes. The participants repeated the 13 conditions, presented in random order, six times on separate days.

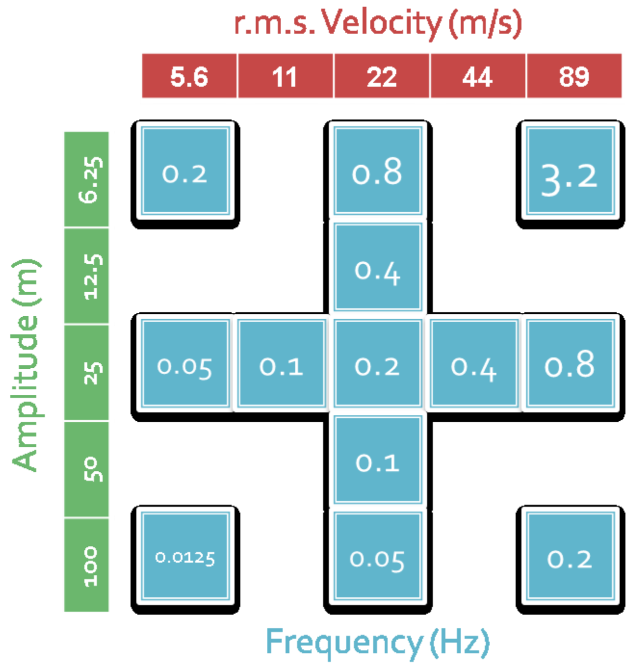


Figure 4.2 An illustration of the 13 conditions of Experiment PS2.

Table 4.2 DOE of Experiment PS2

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

Procedures and Measurements:

In this experiment, the procedure was similar to the Experiment PS1 but with two modifications: (i) the rated perceived speed was no longer restricted as multiple choices of ratios of the reference speed. Instead, the reference speed was assigned as "100 unit per second", and the participants were free to give any integer values to the average speed of the signal stimuli relative to the reference speed (see perceived speed in Chapter 3). (ii) The intensity of vection was measured with a 7-point ratings scale adopted from Webb and Griffin (2003) instead of the previously used 4-point Likert scales (see vection measures in Chapter 3).

4.4 Results

The results of the two perceived speed experiments were shown and analyzed together because of their similarity. The author also hope that by grouping them in the same chapter, there will be less repeated redundancy in the thesis and it would help the readers to focus on the most important information.

In the following sub-sections, results are grouped according to the two main dependent variables: perceived speed and perceived vection. For each dependent variable, the effects of repetitions; the effects of manipulating frequency by varying stimuli's amplitude; and the effects of manipulating frequency by varying stimuli's velocity are presented sequentially.

4.4.1 Perceived Speed

4.4.1.1 Effects of repetitions

The effects of repetitions on average perceived speed collected in the Experiment PS1 are plotted in Figure 4.3. As shown in the figure, a reduction trend could be observed. Since the data were not normally distributed ($p<0.001$, Shapiro-Wilk), non-parametric tests were used. Results of Friedman two-way analyses of variance indicated that the repetition did not significantly affect the perceived speeds (chi-square = 4.224, $p=0.238$). This result is consistent with the plot of median perceived speeds with the 4 repeats (Figure 4.4). However, results of Wilcoxon Signed Rank tests indicated significant difference was found between data collected in the second and third repetitions ($z=-2.084$, $p=0.037$, Wilcoxon). Wilcoxon tests also showed that data collected in the first and second repetitions as well as in the third and fourth repetitions were not significantly different from each other ($z=-0.06$, $p=0.952$; $z=-0.634$, $p=0.526$; respectively). In summary, results of Friedman suggested no effects of repetition while results of Wilcoxon tests suggested to remove the data collected from the first and second trials. In the subsequent analyses, we adopt both approaches for the perceived speed collected in Experiment PS1. In other words, for each participant, data from both the 4 repeats and the last 2 repeats were averaged to get the better mean estimations.

Perceived speed data collected in Experiment PS2 are shown in Figure 4.5 as a function of repetition. The data were not normally distributed (p<0.001, Shapiro-Wilk). Results of both Friedman and Wilcoxon tests indicated no significant (p>0.7 for Friedman; p>0.19 for all pairs of Wilcoxon tests). Therefore, all data from the six repetitions were included in the later analysis. In other words, for each participant, data from the six repeats were averaged to better mean estimations.

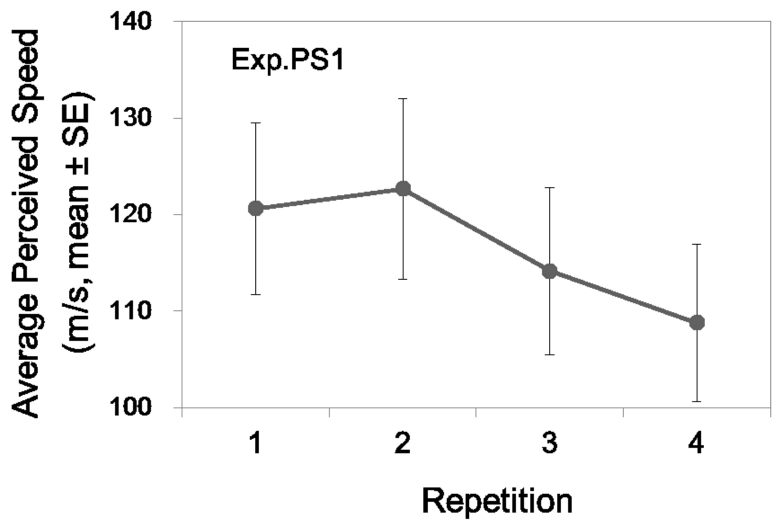


Figure 4.3 Average perceived speeds collected at different repetitions in Experiment PS1.

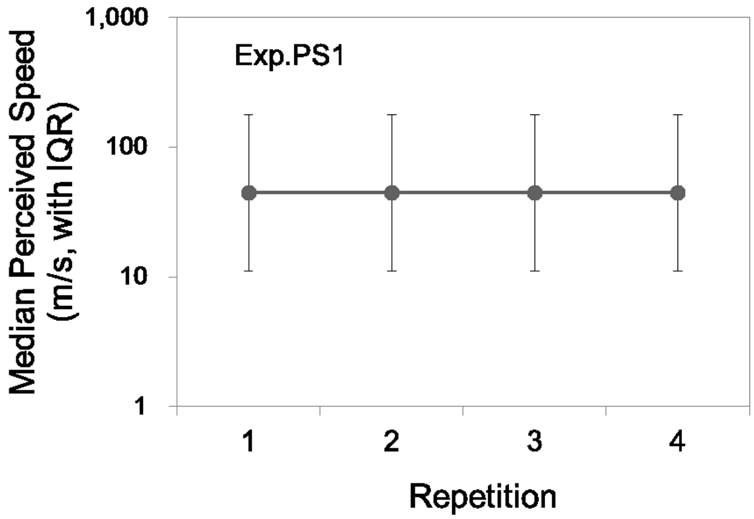


Figure 4.4 Median perceived speeds collected at different repetitions in Experiment PS1.

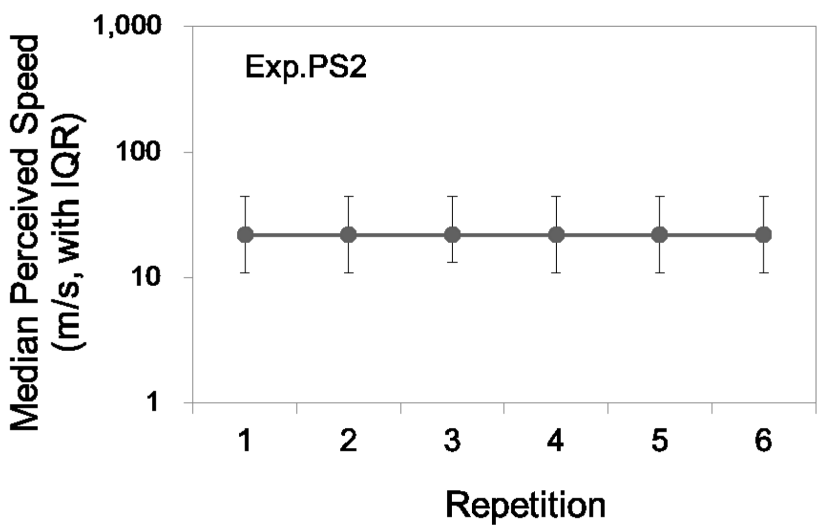


Figure 4.5 Median rated levels of vection collected at different repetitions in Experiment PS2.

4.4.1.2 Effects of frequencies (confounded with amplitudes) under constant r.m.s. velocities

The frequency responses of r.m.s. perceived speed when the r.m.s. velocities of visual motion were kept constant are shown in Figures 4.6(a), 4.6(b) and 4.7 for the two experiments. The r.m.s.

perceived speeds were presented in median rather than in mean because the data were not normally distributed (p<0.001, Shapiro-Wilk). Figures 4.6(a) and 4.6(b) contain the median data extracted from the averaged data from the 4 and 2 repeats, respectively.

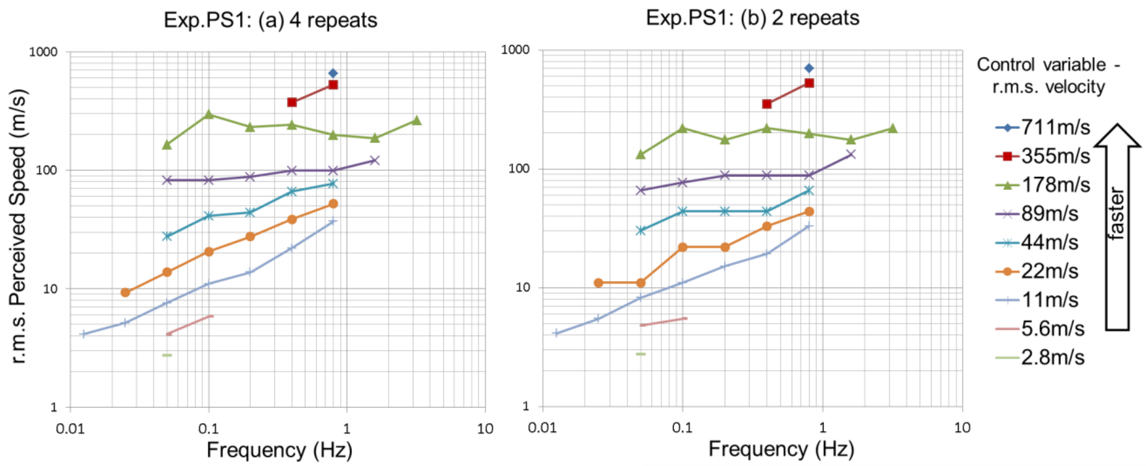


Figure 4.6 Frequency responses of perceived speeds at nine different levels of constant r.m.s. velocities (medians of average data collected in (a) 4 repetitions and (b) 2 repetitions). Data collected in Experiment PS1 using a zooming radial checker-board pattern.

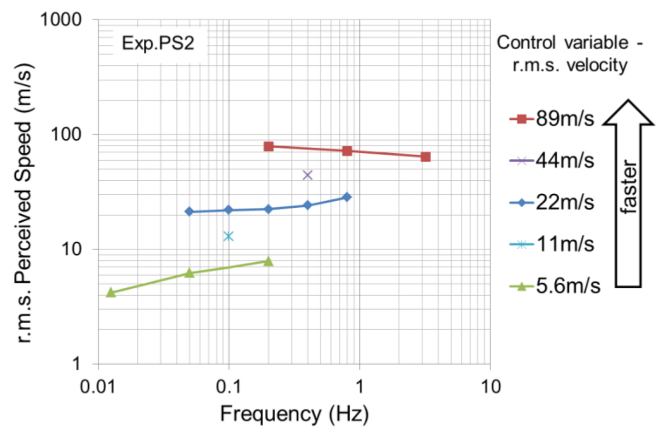


Figure 4.7 Frequency responses of perceived speeds at five different levels of constant r.m.s. velocities (medians of average data collected in 6 repetitions). Data collected in Experiment PS2 using a zooming star field.

Inspections of Figure 4.6(a) and 4.6(b) suggest that mean estimations using 4 repeats and mean estimations using the last 2 repeats produced similar frequency responses. Since tests of Wilcoxon did report a significant difference between perceived speed data collected at repetition two and three, subsequent analyses will use the mean estimations from the last two repeats.

The trends of frequency responses of perceived speed could be separated in two patterns: (i) a flat frequency response when the r.m.s. velocity was kept constant at 89 m/s or above; and (ii) an increasing frequency response when the r.m.s. velocity was kept constant at 44 m/s or below.

Wilcoxon Signed Rank tests were conducted to pairwisely compare the r.m.s. perceived speed at different frequencies on each frequency response. Results are shown in the Appendix 4.1. In general, changes of frequency from 0.05 Hz to 1.6 Hz did not affect the perceived speeds when the r.m.s. velocities were controlled at 89 m/s or above, while significant effects of frequency were found nearly in all pairwise comparisons (among 0.025, 0.05, 0.1, 0.2, 0.4 and 0.8 Hz) with constant r.m.s. velocities of 44 m/s or lower. As explained in Chapter 3, travelling in the virtual visual checker-board patterned tunnel at 89 m/s will mean passing through about 2 black stripes in one second and traveling at 44 m/s will mean passing through about 1 black stripe in one second. So *et al.* (2001a) suggested including spatial frequency as part of a quantifying unit to describe VIMS provoking stimuli. In Chapter 7, data collected in this study will be analyzed using the methodology proposed in So *et al.* (2001a).

Inspections of Figure 4.7 indicated that a flat frequency response when r.m.s. velocities were kept constant at 89 m/s ($p>0.1$, Friedman) and an increasing response when r.m.s. velocities were kept constant at 5.6 m/s ($p<0.001$,Friedman). Such patterns are the same as those obtained in Experiment PS1. This greatly increased the generalizability of the findings as striped patterns and star-field patterns are commonly used in perception experiments (e.g., Duh *et al.,* 2004; Diels and Howarth, 2012; Chow *et al*., 2007; Ji *et al.*, 2009).

To better illustrate the accuracy of perceived speeds, the perceived speeds can be plotted against the actual values for different frequencies for Experiment PS1 as an example (Figure 4.8). If all perceived speeds were estimated accurately, all data points would have followed the x=y diagonal axis of the figure. Inspections of the figure indicate that perceived speed estimations were accurate for stimuli at 0.2 Hz, the same frequency as the reference). For frequencies higher than 0.2 Hz, participants tended to perceive higher speeds than the actual visual motion. On the contrary, for frequencies lower than 0.2 Hz, lower than the actual speeds were perceived. More analyses on the effects of frequency on the accuracy of perceived vection can be found in Section 4.5.2.

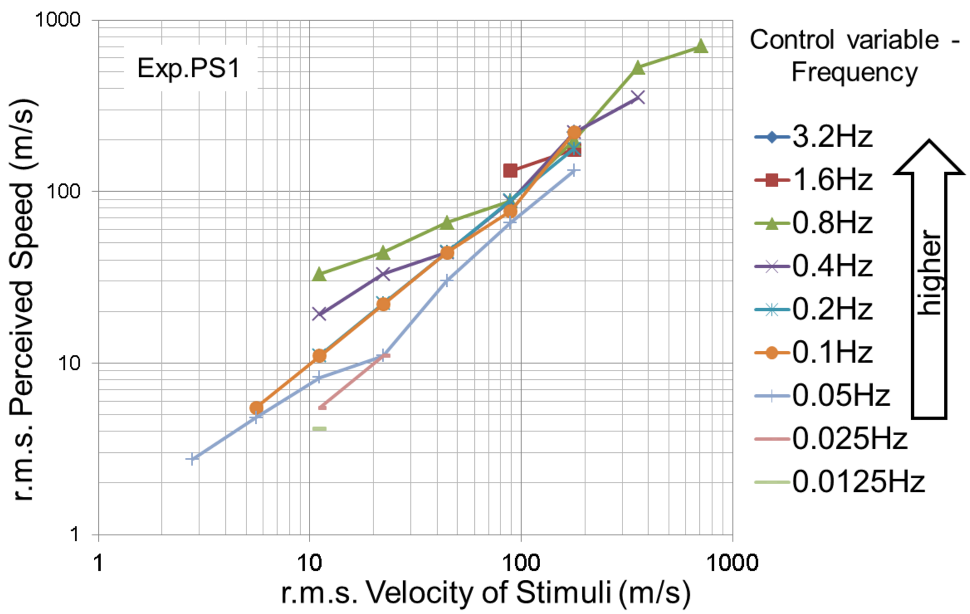


Figure 4.8 The perceived speeds for Experiment PS1 plotted against the actual values for different frequencies to visualize the accuracy of the perceived speeds.

4.4.1.3 Effects of frequencies (confounded with velocities) under constant motion amplitudes

In this section, the same data set will be analyzed but grouped according to the level of visual motion amplitude instead of velocity. Similar to Section 4.4.1.2, mean estimations from the last two repeats will be used in the section. The frequency responses of median r.m.s. perceived speed at different levels of constant visual motion amplitudes are shown in Figure 4.9 and Figure 4.10 for Experiment PS1 and PS2, respectively.

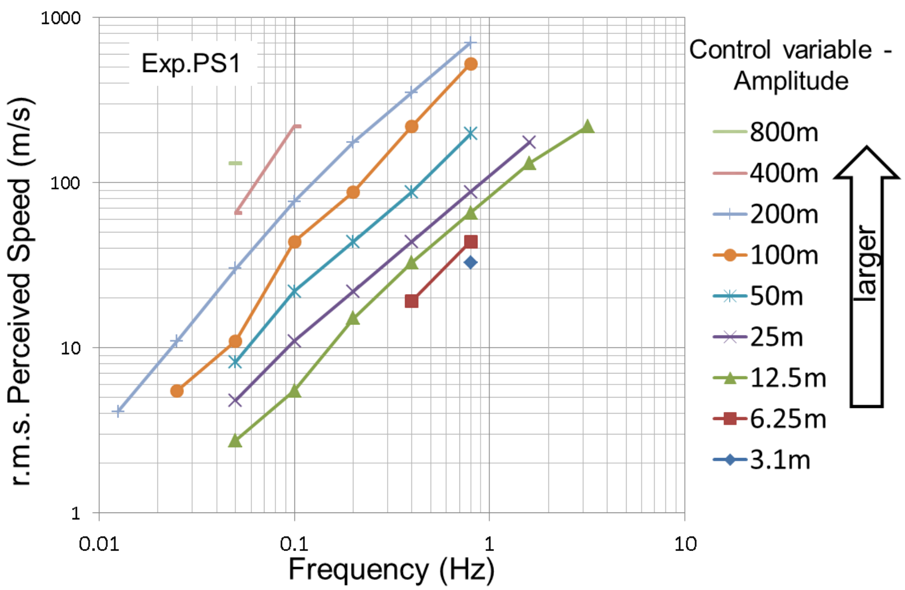


Figure 4.9 Frequency responses of perceived speeds at nine different levels of constant amplitudes (medians of average data collected in 2 repetitons). Data collected in Experiment PS1 using a zooming radial checker-board pattern.

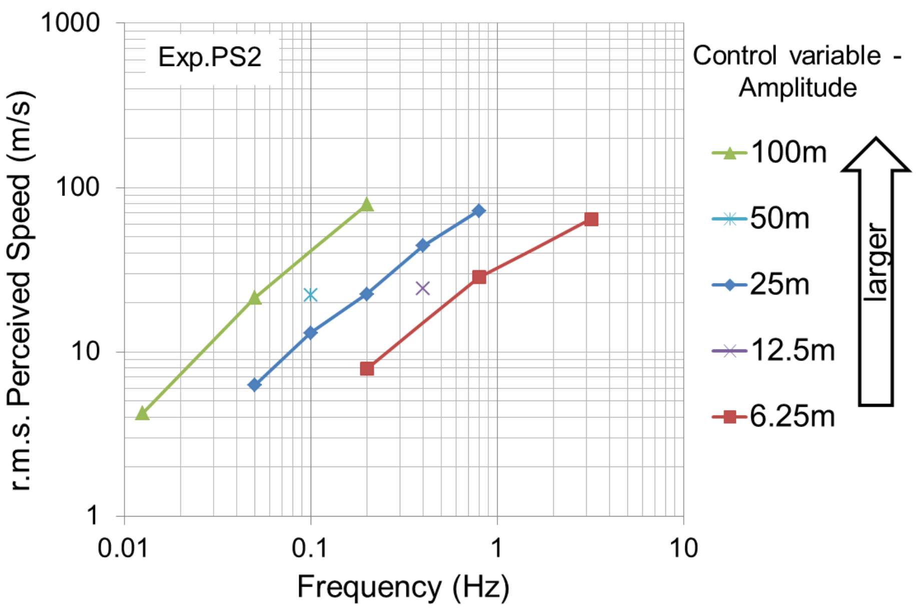


Figure 4.10 Frequency responses of perceived speeds at five different levels of constant amplitudes (medians of average data collected in 6 repetitions). Data collected in Experiment PS2 using a zooming star field.

Inspections of Figures 4.9 and 4.10 indicate the trends of increasing perceived speeds with increasing frequencies for all levels of amplitudes. This is not surprising because when amplitude was kept constant, frequencies were confounded with velocities. Consequently, as frequencies increased, the r.m.s. velocities of the visual stimuli would also increase which in turn would cause the perceived velocity to increase.

Wilcoxon Signed Rank tests were conducted to pairwisely compare the r.m.s. perceived speed within each frequency response curve. Results are shown in the Appendix 4.2. Results from all comparisons are significant indicating a strong influence of frequency on perceived speeds. This pattern is clearly different from the flat response when r.m.s. velocity was kept at 89 m/s or above. Since both can be referred to as frequency responses of perceived speeds, the current findings demand a better way of presenting frequency responses – see Chapter 6.

4.4.2 Perceived Vection

4.4.2.1 Effects of repetitions

Perceived vection data collected in Experiments PS1 and PS2 are plotted as functions of repetition in the Figure 4.11 and Figure 4.12, respectively.

Results of Friedman two-way analyses of variance indicated that repetitions had significant effects on vection collected in Experiment PS1 (Chi-square=14.072, p=0.003). The effects of repetition still existed after the data in repetition one had been taken out from the pool (chi-square=16.321, p<0.001). When data collected in repetition one and two were removed, effects of repetition became non-significance (Chi-square=1.163, p=0.281, Friedman). The significant effect of repeat is not obviously observable in Figure 4.11. Further investigations reveal that although data collected from most conditions did not show a significant effect of repetition, data from 6 conditions were affected significantly by repetitions and after removing the first two repeats, the effects of repetition became non-significant. Consequently, mean estimations using data from the last two repetitions were used in subsequent analyses. Interestingly, these 6 conditions were with high frequencies and fast velocities. Future work to investigate this effect of repeats are desirable.

For the Experiment PS2, effects of repetition on vection was not significant (p>0.05, Friedman). Therefore, all data were included in the subsequent analysis. In other words, data from all 6 repeats were averaged to form better mean estimations.

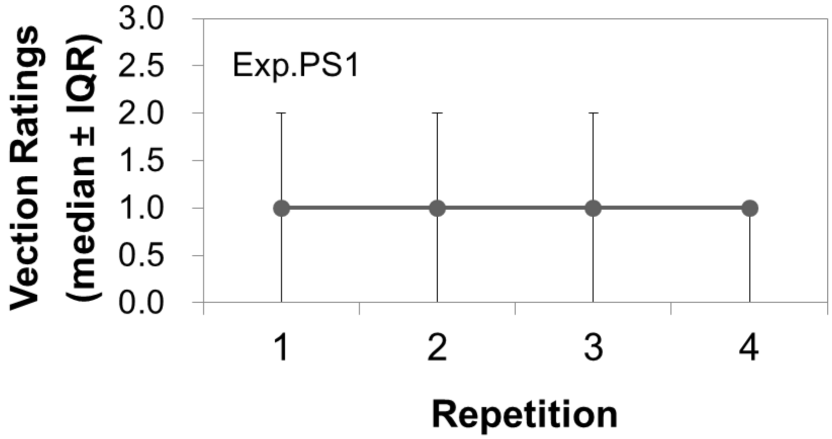


Figure 4.11 Median vection data with inter-quartile ranges plotted as functions of repetitions (data collected in Experiment PS1).

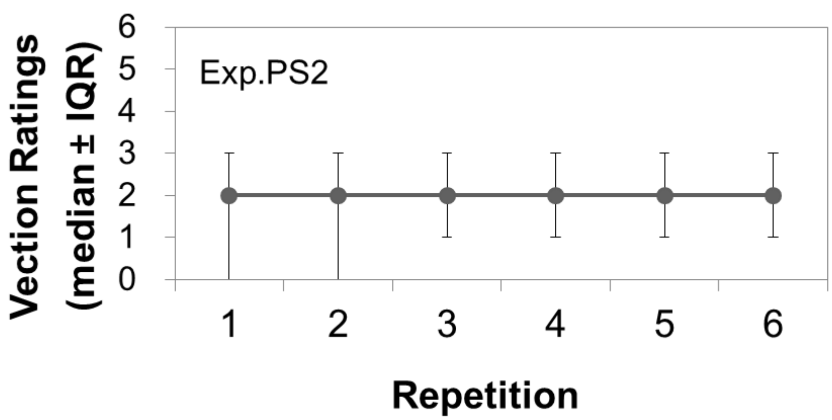


Figure 4.12 Median vection data with inter-quartile ranges plotted as functions of repetitions (data collected in Experiment PS2).

4.4.2.2 Effects of frequencies (confounded with amplitudes) under constant r.m.s. velocities

The frequency responses of median perceived self-motion (vection) with visual oscillations of constant r.m.s. velocities are shown in Figure 4.13 and Figure 4.14 for Experiment PS1 and PS2, respectively.

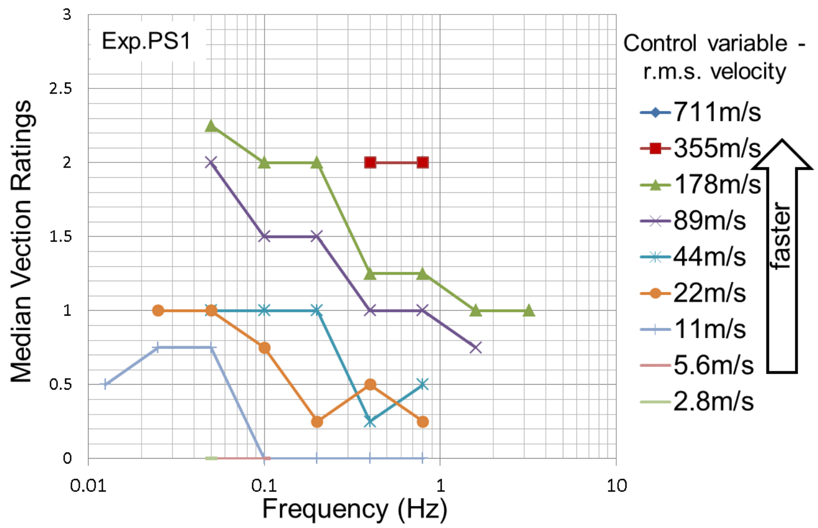


Figure 4.13 Median vection as functions of frequencies when the velocities of the visual oscillations were kept constant (data collected in Experiment PS1).

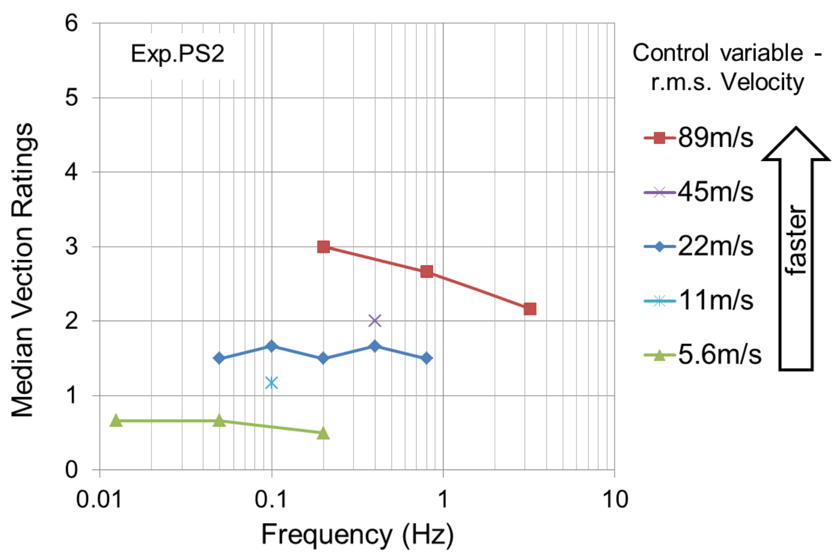


Figure 4.14 Median vection as functions of frequencies when the velocities of the visual oscillations were kept constant (data collected in Experiment PS2).

When r.m.s. velocities were kept constant, vection reduced with increasing frequency in both Experiments PS1 and PS2. Such negative effects of frequency on vection tended to be larger as the constant r.m.s. velocities of the stimuli were 89 m/s or faster (curves are more inclined at higher velocities). Results of Friedman two-way analyses of variance indicated that the reducing trends were significant when velocity was kept constant at 5.6, 11, and 89 m/s (see Appendix 4.3).

4.4.2.3 Effects of frequencies (confounded with velocities) under constant motion amplitudes

The frequency responses of vection (medians) when the amplitudes of visual motion were kept constant are shown in Figure 4.15.

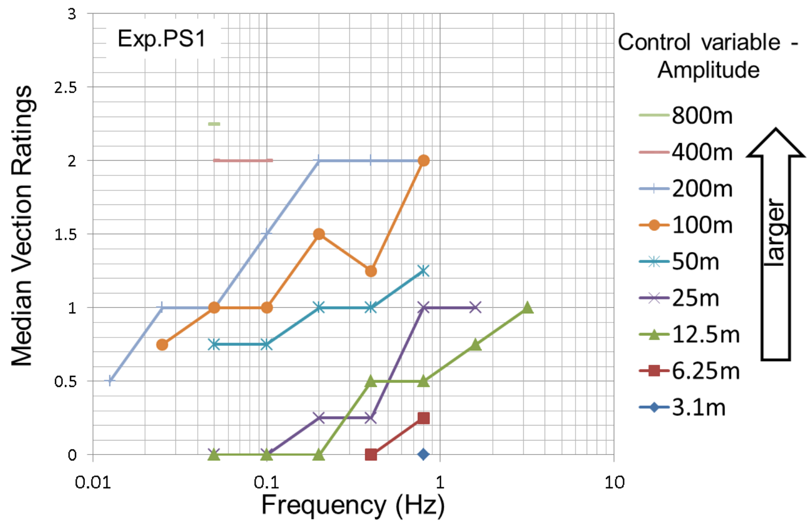


Figure 4.15 Median vection as functions of frequencies when the amplitudes of the visual oscillations were kept constant (data collected in Experiment PS1).

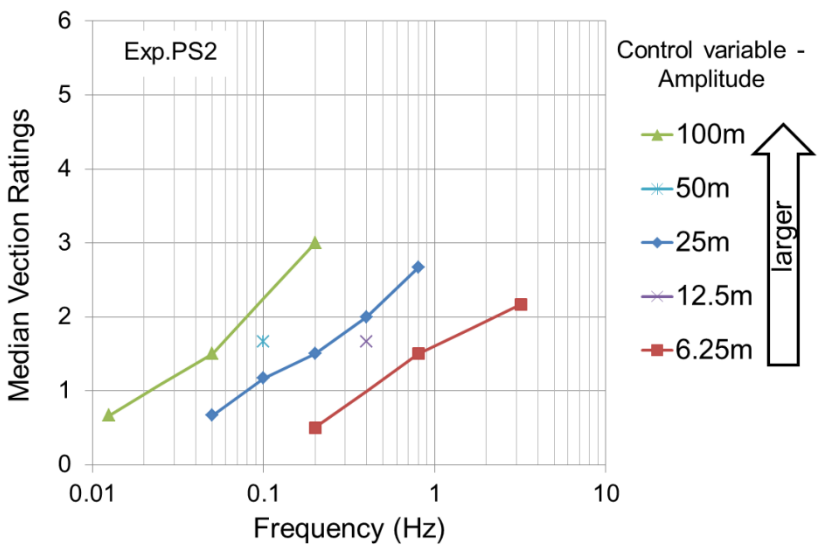


Figure 4.16 Median vection as functions of frequencies when the amplitudes of the visual oscillations were kept constant (data collected in Experiment PS2).

Inspections of both figures indicate that the vection increased with increasing frequencies. Results of Friedman two-way analyses of variances indicate that these increasing trends were significant at 6.25, 12.5, 25, 50, 100 and 200 m. Wilcoxon Signed Rank tests had also been conducted to pairwisely and the statistics are shown in the Appendix 4.4. Results of Wilcoxon tests are consistent with those in Friedman. It is interesting to see that the frequency responses of vection had opposite trends when velocity or amplitude of the visual stimuli was kept constant. This, again, supports the two-frequency-response hypothesis.

In addition, it is interesting to note that the participants did not confuse vection and perceived speed. If they had confused the two, responses of vection and perceived speed should have looked very similar. However, this is not the case. They are very different. Therefore, the distinctively different frequency responses of vection and perceived speed suggest that the participants were able to reliably separate their perception between vection and perceived speed of the visual motion.

4.5 Discussion

4.5.1 Frequency Responses of Perceived Speed and Perceived Vection

Results of both Experiments PS1 and PS2 showed that whe watching visual oscillation along the fore-and-aft axis, participants' perceived speed exhibited two different patterns as the frequency of the oscillation changed. In other words, two frequency responses were obtained. One type of patterns is that when keeping the r.m.s. velocities of the stimuli constant, the frequency response curves are generally flat between 0.05 Hz to 1.6 Hz but they gradually take on an increase trend with increasing frequency for r.m.s. velocities at 22 m/s or below. For the other pattern, perceived speeds increase significantly with increasing frequency when the amplitudes of the oscillating stimuli are kept constant. These findings are new and original since, to the best of our knowledge, little studies have been worked on speed perception using oscillating visual motion as stimuli. Effects of temporal frequency of visual oscillations on perceived speed were unknown before the current study.

Rated levels of self-motion illusion (vection) also exhibited two types of frequency responses. One type is that when keeping r.m.s. velocities of the visual motion constant, vection levels decreases as frequency increases. This type of frequency response is consistent with the results of several previous studies (Duh *et al*., 2004; Chow, 2008; Chen *et al*., 2012; Diels and Howarth, 2012). The other type of pattern is that, when the amplitudes of the visual oscillations are kept constant, vection initially increases with frequency and then saturates. This finding is consistent with the literature (Previc *et al*., 1993; So *et al*., 2001; Chen, 2006). Since both types of frequency responses have been referred as frequency responses, this finding confirms and explains the conflicting results in the literature. This is new and original.

In summary, perceived speed and vection data obtained in the two experiments demonstrate two completely distinct patterns of frequency responses in support to the two-frequency-response hypothesis. The hypothesis states that frequency-dependence characteristics of vection and perceived speed for viewing oscillating scenes would be different if the frequencies of stimuli are manipulated differently: (i) by varying amplitudes but keeping r.m.s. velocities constant; or (ii) by changing r.m.s. velocities but keeping amplitudes the same.

4.5.2 Analyzing the Accuracy of Perceived Speed

4.5.2.1 Perception accuracy and bias

The accuracy of perceived speeds was measured by the 'perception bias' as defined as follows:

$$\text{Perception Bias} = \log_2 (\text{Perceived speed} / \text{Actual speed})$$

A perfect perception will result in zero perception bias. A positive bias means overestimation and a negative value means underestimation.

Perception bias collected in both Experiments PS1 and PS2 at different combinations of frequencies and velocity are shown in Figure 4.17. Inspections of the figure indicate that at r.m.s. velocities of 89 m/s or above, the biases converge to zero suggesting that participants were able to perceive the speed of fast visual oscillations more accurately than slower oscillation. In Experiment PS1, exposure to an visual stimuli at r.m.s. velocity of 89 m/s was like travelling inside a long tunnel of 5 m diameter with consecutive 20m sections of the tunnel painted in black and white alternatively. In other words, if you were traveling at 89 m/s, you would have passed through about 2 black and 2 white sections of the tunnel in one second.

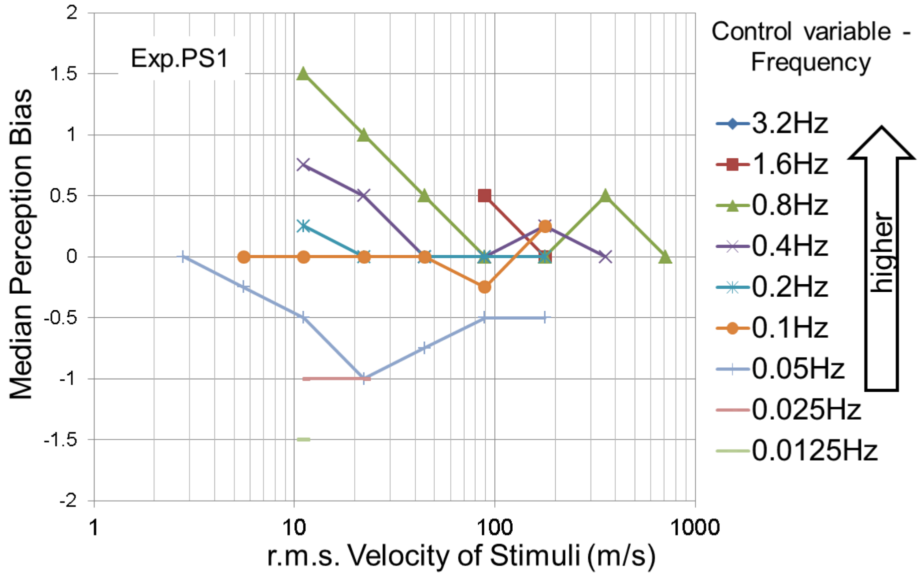


Figure 4.17 Perception bias for the perceived speeds plotted against the actual speeds of stimuli at different levels of frequency. (Data collected from Experiment PS1 was used as an illustration).

For perception bias associated with oscillations at r.m.s. velocities lower than 89 m/s, an interesting and significant trend can be observed (Figure 4.17). Participants would overestimate the speed of visual motion when the frequencies of oscillations were 0.2 Hz or higher but underestimate when the frequencies were 0.1 Hz or lower. In other words, the perception bias reduces from positive to zero to negative as the frequencies of the visual oscillations whose speeds were being estimated reduced from 3.2 Hz to 0.1 Hz to 0.0125 Hz.

It is not difficult to understand why higher frequencies (0.2 Hz or higher) make the visual motion look faster while lower frequencies do the reverse. Since the perceived speeds were measured as ratio scaling data using fix-modules method with a 0.2Hz, 44 m/s visual oscillation as the reference, it is easy to understand why the perception bias is close to zero with visual oscliiations at 0.2 Hz.

4.5.2.2 Influence of the presence of vection on perceived speed

In this section, the association between rated vection and perceived speed are analyzed. When the visual stimuli was oscillating at 0.8 Hz, for instance, vection and perception bias was negatively correlated ($p<0.05$, coefficient = -0.244, Spearman). This suggests that the presence of vection was associated with perceived slowing down of the visual motion which is consistent with the definition of vection – when someone perceive saturation vection, he or she should feel that the visual motion appear to be stationary and his or her body was moving in the opposite direction of the visual motion (Webb and Griffin, 2002). The small correlation coefficient indicates that there are many other factors influencing the vection and perceived speeds and one of them would be inter-subject variability. The scatter plot between vection and perception bias of participants of Experiment PS1 is shown in Figure 4.18. However, the correlations between vection and perception bias are subject to vary as a function of stimuli's velocities and frequencies, which will be discussed in the section 4.5.3.

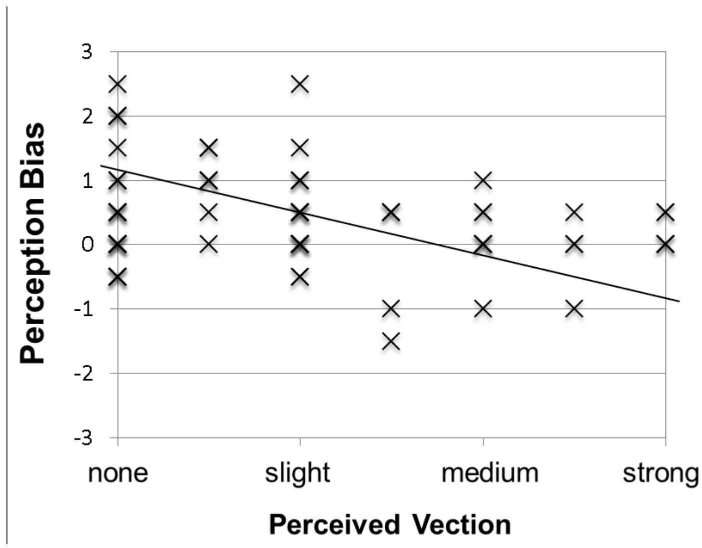


Figure 4.18 A scatter plot between vection and perception bias when viewing visual stimuli oscillating at 0.8 Hz along the fore-and-aft axis. Data collected in Experiment PS1.

4.5.3 Comparing the Main Effects of Velocity, Frequency, and Amplitude

4.5.3.1 Correlations

Generally, perceived speed is significantly and positively correlated with velocity (Spearman's rho=0.94, $p<0.001$), with frequency (rho=0.63, $p<0.001$), and with amplitude (rho=0.298, p<0.001). Vection is also significantly and positively correlated with velocity (rho=0.561, p<0.001), with amplitude (rho=0.463, p<0.001), and but not with frequency (rho=0.085, p>0.1).

By comparing the correlation coefficients, both perceived speed and vection are subjected to more association with velocity than amplitude and frequency of the visual stimuli. At the same time, it is also worth noting that perceived speed had a higher correlation coefficient with frequency than amplitude, and the difference is more than double. For vection, it had a higher correlation with amplitude than frequency and the difference is more than 5 times. The non-significance of correlation between vection and frequency reflected the fact that frequency has opposite effects on vection when keeping velocity or amplitude constant (section 4.5.1).

The correlation relationship between vection and perceived speed was analysed and the results are listed in Table 4.3. In general, vection and perceived speed were significantly and positively correlated (rho = 0.511, p<0.001). However, this relationship varied in specific situations. In those with constant r.m.s. velocities, the strengths of correlation between perceived speed and vection were small and sometimes not significant (|rho|<0.3). However, when the amplitudes or frequencies were kept constant, the correlations between vection and perceived speed were all both statistically significant and much stronger (rho=0.373 to 0.693).

Table 4.3 Correlations between vection and perceived speeds at different conditions with constant velocities, constant amplitudes and constant frequencies.

Vection v.s. PS						
Spearman	**Pooled**	**r.m.s.Vel =11m/s**	**r.m.s.Vel =22m/s**	**r.m.s.Vel =44m/s**	**r.m.s.Vel =89m/s**	**r.m.s.Vel =178m/s**
rho	**0.511****	**-0.264***	**-0.23**	**-0.06**	**0.06**	**0.12**
Sig.	***0.00***	***0.03***	***0.08***	***0.66***	***0.64***	***0.31***
		Amp=12.5m	**Amp=25m**	**Amp=50m**	**Amp=100m**	**Amp=200m**
rho		**0.373****	**0.397****	**0.395****	**0.442****	**0.600****
Sig.		***0.00***	***0.00***	***0.00***	***0.00***	***0.00***
		Freq=0.05Hz	**Freq=0.1Hz**	**Freq=0.2Hz**	**Freq=0.4Hz**	**Freq=0.8Hz**
rho		**0.625****	**0.592****	**0.595****	**0.693****	**0.692****
Sig.		***0.00***	***0.00***	***0.00***	***0.00***	***0.00***

Combining the detailed information about the correlation between vection and perceived speed in Table 3, it may imply that people who experience higher vection tend to also perceive a faster speed. However this result may differ in different situations. For examples, when viewing stimuli oscillating at 11 m/s, the presence of vection was associated with underestimation of the perceived speed. To illustrate the interaction effects, distributions of perception bias and mean vection perception in each condition in Experiment PS1 are plotted in Figure 4.19.

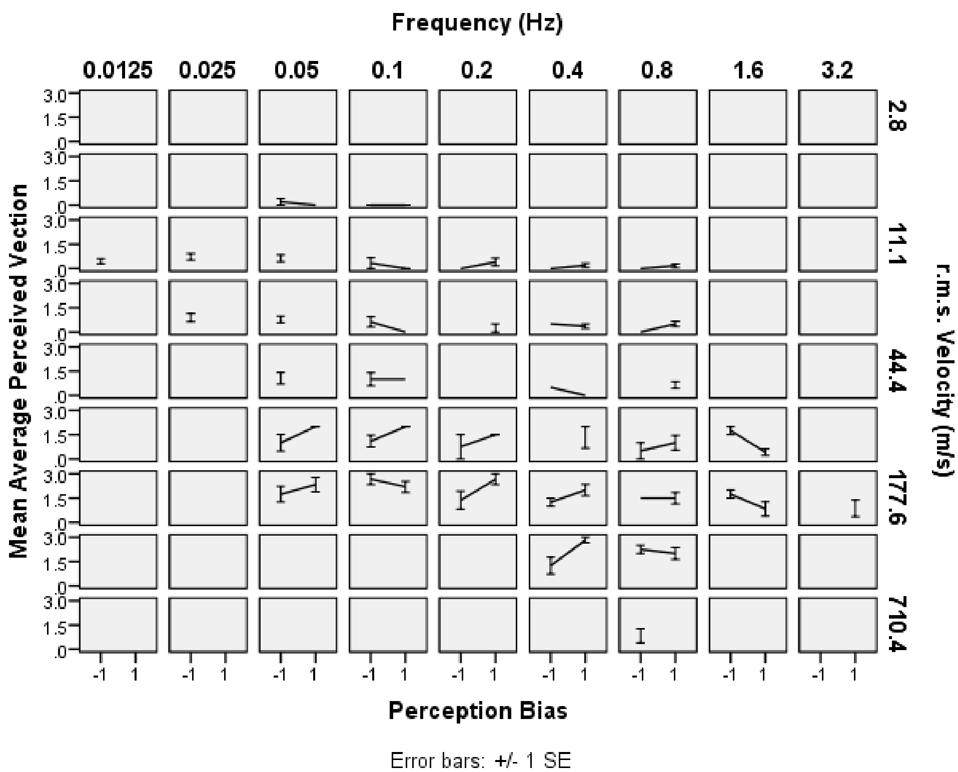


Figure 4.19 Distributions of the associations between vection and perception bias (-1: underestimation; +1: overestimation) of perceived speeds as functions of velocities and frequencies.

4.5.3.2 Relationships among velocity, amplitude, and frequency

For a sine wave motion, displacement $d = A \cdot \sin(2\pi \cdot f \cdot t)$, (notion: A is amplitude of displacement, f is frequency, and t is time). Take derivative of d, so we get velocity $V = 2\pi \cdot f \cdot A \cdot \cos(2\pi f \cdot t)$. Therefore,

$$V_{r.m.s.} = \frac{V_{max}}{\sqrt{2}} = \frac{2\pi \cdot f \cdot A}{\sqrt{2}} = \frac{2\pi \cdot A}{\sqrt{2} \cdot T} \quad ,$$

where T is the cycle duration of the sine wave motion. Namely, velocity is a function of the temporal frequency (or cycle duration) and the amplitude of displacement.

Obviously, velocity, amplitude, and frequency are not independent. In other words, it is not possible to change one of the three variables without affecting the other two. This is also one of the main reasons why previous studies on frequency responses had confounding effects with either velocity or amplitude or both.

From a physical unit standpoint, according to the International System of Units (SI), the unit of velocity is measured in a meter per second, amplitude's is meter, and frequency's is hertz (reciprocal of second). The unit of velocity is derived from the unit of length (meter) and the unit of time (second). Therefore, while frequency only carries information of time and amplitude only of space, velocity carries information from both time and space. Since self-motion awareness and recognition is a dynamic spatio-temporal process, only velocity is capable of providing sufficient information to complete the whole process. It may be the reason why our results show that velocity is the dominant factor affecting vection and perceived speed, comparing with amplitude and frequency. Also note that the correlation coefficient between perceived speed and velocity (rho=0.94) is equal to the sum of the correlation coefficient between perceived speed and frequency (rho=0.63) and the one between perceived speed and amplitude (rho=0.298). This relation is also true for vection and perception bias.

4.5.4 Implications on Understandings of Visually Induced Motion Sickness (VIMS)

Following the previous discussion of the effects of velocity, amplitude, and frequency of visual stimuli on vection and the fact that vection and motion sickness are positively correlated (Hettinger and Riccio, 1992), it is reasonable to hypothesize that motion sickness when viewing oscillating stimulus would be affected by these three parameters in a similar fashion as vection. In other words, the velocity of visual motion should have the strongest effect on VIMS, followed by the amplitude and the frequency should be the least effective factor. In the next chapter, the exposure duration to selected visual stimuli would be extended to study their effects on levels of VIMS.

4.5.5 Consistency with Knowledge on Human Visual Systems

In the results of Experiments PS1 and PS2, the dominant role of velocity in determining visual motion perception is consistently showing its evidence. This finding is also consistent with previous neurophysiological researches (e.g., Rodman and Albright, 1987; Perrone and Thiele, 2001). These studies report that visual neurons in the cortical areas V1 and Middle Temporal (MT) are velocity tuned during the recognition of visual motion. Both speed (magnitude) and direction of a movement can be independently selected by visual neurons (Schrater *et al*., 2000; Bradley and Goyal, 2008; Burr and Thompson, 2011). In other words, our visual motion perception pathways are dominated by specific velocity-tuned neural circuits. Not surprising, velocity has been found to be the major dominating factors affecting perceived speed and vection.

However, previous literature cannot explain our results when r.m.s. velocity was kept constant and participants obtained different outcomes for perceived speed and vection. The cortical mechanism of temporal frequency and amplitude is yet not clear. Are there another two kinds of visual neural cells that detect space/depth (amplitude), responsible for time elapse (frequency), other than velocity? Whether temporal frequency and amplitude are only two elements involved in the computation of velocity in visual system, in which case velocity is the ultimate product to be perceived / recognized, or they are two independent factors, together with velocity that affect visual motion perception? Although the results of this paper implies that velocity, frequency, and amplitude are fundamentally different and can be independently perceived by the visual system, further neurophysiological studies are required to answer these research conundrums.

4.6 Conclusions

In this chapter, two distinctive patterns of the frequency responses of vection and perceived speed have been identified when the frequency of visual stimuli were manipulated using amplitude or velocity. Two experiments using different types of visual motions are reported and their results are consistent with each other. Hence, strengthening the generalizability of the results. The current finding is important because in the current literature, these two patterns of frequency responses are both referred to as one type. This research helps to alert researchers the need to be aware of such distinctive discrepancy in frequency responses. Although velocity, frequency, and amplitude are dependent within the context of oscillatory movement, results reported in this chapter indicates that these three parameters have independent effects on perceived speed or vection. In the next chapter, the two-frequency-response hypothesis will be tested on VIMS.

CHAPTER 5: FREQUENCY RESPONSES OF VISUALLY INDUCED MOTION SICKNESS WHEN VIEWING STIMULI OSCILLATING ALONG FORE-AND-AFT AXIS: KEEPING R.M.S. VELOCITY CONSTANT V.S. KEEPING AMPLITUDE CONSTANT

SUMMARY

The frequency responses of perceived speed and vection are presented in Chapter 4. Results supported the two-frequency-hypotheses indicating that by keeping the stimuli's velocities constant or stimuli's amplitudes constant will result in different frequency responses for perceived speed and vection. In particular, perceive speed would mostly have flat responses when velocity was kept constant at 88.9 m/s or higher but when amplitudes were held constant, perceive speed will increase significantly with increasing frequencies in all combinations with amplitudes ranging from 6.25 m to 200m ($p<0.01$, Friedman). At 88.9 m/s, participants travelled pass two pairs of black-and-white stripe patterns in one second. For vection, the differences are even greater. When velocity was held constant, vection reduced significantly with increasing frequency ($p<0.01$, Friedman) but when amplitude was held constant, vection increased significantly with increasing frequency ($p<0.01$, Friedman). This leads to the logical question about whether the two-frequency-response hypothesis also applied to levels of VIMS.

In Chapter 5, two experiments are reported to test the two-frequency-response hypothesis with measurements of VIMS. In the first experiment (Experiment VIMS1), twelve participants (7 females and 5 males, aged between 19 to 24 years old) were exposed to the zooming radial checker-board pattern (used in Experiment PS1) with r.m.s velocity kept constant at 44.5 m/s. The second experiment (Experiment VIMS2) extended Experiment VIMS1 to test conditions with constant velocity and constant amplitude. Experiment VIMS2 used the zooming random-dots

pattern used in Experiment PS2). Results from both experiments supported the two-frequency-response hypothesis.

5.1 Introduction and motivations for Experiments VIMS1 and VIMS2

About one-third of Hong Kong Chinese population are susceptible to motion sickness (So *et al.,* 1999). This figure is consistent with results of survey conducted in United Kingdom (Griffin, 1990). Viewing wide field-of-view (FOV) visual motion, in the absence of appropriate physical motion, could induce illusion of self-motion (vection). Prolong exposure to such visual stimuli could cause symptoms of motion sickness among susceptible viewers (Lo and So, 2001). This type of motion sickness has been referred to as visually induced motion sickness (VIMS) (e.g., Bos *et al.*, 2008, 2010; Diels and Howarth, 2011; Kennedy *et al.*, 2010; So and Ujike, 2010). With increasing accessibility to virtual reality displays and wide FOV HDTVs, concerns for VIMS associated with exposure to video games led to the declaration of International Workshop Agreement 3 on image safety (IWA, 2005). As one of the theme topics in this workshop, VIMS has attracted worldwide attention and more studies to determine the causes of VIMS are urged. In particular, more research to determine repeatable relationships between visual stimuli and VIMS are desirable.

Duh *et al*. (2004) proposed a cross-over frequency (COF) model for VIMS and predicted that the level of VIMS would be most serious when watching visual motion oscillating at around 0.06 Hz. Based upon the sensory conflict theory (Reason, 1978), Duh and his colleagues argued that for self-motion perception, humans are sensitive to both visual motion and physical motion at 0.06 Hz. Therefore, Duh argued that when exposed to 'conflicting' visual and physical motion cues at 0.06 Hz, people prone to be bewildered and hence experience the highest level of VIMS due to the greatest mismatch of visual and physical motion cues. Though it is not the aim of this thesis to comment on the validity of the COF model for VIMS, it is critical to mention Duh's work, which clearly pointed out the importance of studying VIMS as a function of visual motions of different frequencies. The two experiments described in this chapter measured the frequency responses of VIMS to translational visual oscillations along the fore-and-aft axis. The choice of fore-and-aft axis is because during navigation in most computer games with 3D virtual environments (e.g., flight simulator; car simulator; combat/action games), moving forward and backward is inevitably the most frequent direction of motion.

Besides the importance of studying frequency responses of VIMS, a review of literature indicates that reports concerning how levels of VIMS vary with visual motions of different frequencies have been contradicting. Duh and his colleagues proposed that VIMS peaked when watching visual motion with energy at around 0.06Hz. The finding of 0.06 Hz is consistent with Lin *et al*. (2005). However, Diels and Howarth (2012) reported that VIMS peaked at 0.2Hz instead of 0.06Hz when watching linear zooming visual oscillation. The finding of 0.2 Hz is consistent with Chen (2006). The difference in findings warrants the current studies. Furthermore, both Duh *et al*. (2004) and Diels and Howarth (2012) kept the r.m.s. velocity of their visual oscillations constant and varied the oscillation amplitudes to manipulate the changes in visual motion frequency. In 2001, So and his colleagues studied VIMS associated with navigating through virtual environments and proposed that VIMS would not change if the velocity of navigation was kept constant (So *et al*., 2001a). This prediction goes against the results of both Duh *et al*. (2004) and Diels and Howarth (2012) and adds confusion to the existing contradiction. Further study is desirable.

In addition, the peaks (whether 0.06 Hz or 0.2 Hz) of VIMS for fore-and-aft visual motion with constant r.m.s. velocity has suffered some limitations in their construct validity. Duh *et al.* (2004) constructed their COF hypothesis using data with stimuli rotating in roll axis, verified the COF hypothesis with stimuli rotating in yaw axis and finally generalized the peak of VIMS at 0.06 Hz to exposure to visual motion in all axes through the biological theory behind COF hypothesis. While the author understand the logic of COF and greatly appreciate the originality of COF hypothesis, the process of verifying the frequency response of VIMS with a peak at 0.06Hz does need further work.

On the other hand, Diels and Howarth (2012) combined results from two separate experiments with two different groups of participants in order to report the peak of VIMS at 0.2 Hz because one experiment investigated stimuli with 0.2 Hz or below and the second experiment investigated stimuli with 0.2 Hz or above. Given the importance of the frequency characteristics of VIMS, more robust findings from one single experiment are valuable.

Duh *et al.* (2004) used an oscillating striped pattern while Diels and Howarth (2012) used a zooming star-field. In the first experiment, we used a zooming radial striped checker-board pattern which is a combination of stimuli used by Duh and Diels. In the second experiment, we adopted the same stimulus used in Diels and Howarth (2012).

5.2 Hypothesis

In the last chapter, the two-frequency-response hypothesis has been verified to be true for perceived vection and perceived speed. Therefore, it was hypothesized that the two-frequency-response hypothesis will also be held for VIMS reported while watching visual oscillation along the fore-and-aft axis, namely (i) levels of VIMS should be independent of frequency if the r.m.s. velocity is kept constant, and (ii) levels of VIMS should be dependent of frequency if the amplitude is kept constant.

5.3 Methods

Unlike measurements of perceive speed and vection, participants cannot be exposed to more than one stimulus on the same day without adaptation effect. In fact, to reduce the effects of adaptation, in Experiments VIMS1 and VIMS2, participants need to rest for 7 days on average between each exposure. This greatly increased the experimental time and, hence, the number of conditions in Experiments VIMS1 and VIMS2 had to be optimized.

5.3.1 Methods of Experiment VIMS1

Participants

Twelve healthy university students (7 females), aged between 19 to 24 years, participated in this experiment. All of them were recruited by posting an advertisement online exposed to the entire student community in HKUST. They were all new to virtual realty experiments. All participants had normal or corrected-to-normal vision. Their susceptibility was measured using Motion Sickness Susceptibility Questionnaire (MSSQ) and had a mean percentile score of 62%, which indicates that the sample is slightly more susceptible than the normal population (Golding, 1998). Prior to the experiment, all participants read and signed a consent form approved by the Human Subject Committee at the Hong Kong University of Science and Technology.

Apparatus and Stimulus

The Experiment VIMS1 applied the Setup 1 and the virtual tunnel stimuli described in Chapter 3. The participants stood at the centre of the cylindrical screen area, with a viewing distance of 1.1 metres. The stimuli projected onto the screen with a FOV of 200º (h) x 50º (v) oscillated along the fore-and-aft axis (see Chapter 3 for more details). Each participant wore an acoustic headset with an electromagnetic receiver fixed on it to measure his postural disturbance (Polhemus 3 Space Fastrack system, Polhemus Inc., USA; refer to the section of postural measures in Chapter 3).

Experimental Design

The temporal frequency of the sinusoidal-oscillating visual stimulus was manipulated at five different levels (0, 0.05, 0.1, 0.2, and 0.8 Hz) as the independent variable of this experiment. The dependent variables were nausea ratings, SSQ scores, vection ratings, and postural sway. The r.m.s. velocity of the visual oscillation was controlled at a constant level of 44.5 m/s. Excluding the stationary condition (the 0 Hz condition), the amplitudes of the oscillations were co-varying with the frequencies, ranging from 12.5 m to 200 m. Each participant was exposed to all five conditions in randomized order. There was, on average, one-week separation between any two successive conditions to cope with the adaptation effect. To help readers to visualize the visual oscillation at 44.5 m/s, the readers are reminded that the participants were 'virtually' and 'visually' travelling through a tunnel of 5 meter diameter with alternating black and white radial stripes each span 20 meters along the tunnel. In other words, at 44.5 m/s, the participants would pass through about 1 pair of black-and-white stripes per second (see Chapter 3 for more details). This highlights the need for including a standard measure of scene complexity when describing the visual stimuli. So *et al.* (2001a) proposed such a unit called 'spatial velocity' and in Chapter 7 in this thesis, the data collected in this study are re-analyzed using the methodology proposed in So *et al.* (2001a) to formulate a does value to relate the visual stimuli and levels of nausea.

Procedures and Measurements

In each trial, participants were exposed a visual oscillation at one of the five frequencies for 30 minutes. Participants were asked to look straight ahead at the oscillation with their eyes fixated at the center of the oscillation (normal blinks were allowed). At 5-minute intervals, participants were asked to verbally rate their sensation of vection and nausea respectively. Nausea was measured using a 7-point Likert scale adopted from Golding and Kerguelen (1992). Vection was also measured using a 7-point Likert scale adopted from Chow (2008) and Webb and Griffin (2003). Before and after the exposure, participants completed a pre-exposure and post-exposure simulator sickness questionnaire (SSQ) adopted from Kennedy *et al.* (1993). The postural sways were also measured during the exposure. The detailed methods are described in Chapter 3.

5.3.2 Methods of Experiment VIMS2

Participants

Thirteen healthy university students (7 females), aged between 18 to 25 years, participated in this experiment. All of them were recruited from advertising online and no one had participated in Experiment VIMS1. Their MSSQ had an average percentile score of 49.8%, which indicates that the sample is representative in terms of the susceptibility as the normal population (Golding, 1998). All participants had normal or corrected-to-normal vision. They read and signed a consent form before the start of the experiment.

Apparatus and Stimulus

Experiment VIMS2 used the Setup 2 and the random dots stimuli described in Chapter 3. The participants were sitting on a back-supported chair fixed at the centre of the 3D screen, with his/her head rested on a chin-rest mounted on the table in front (details refer to Chapter 3). This setting aimed to be as close as to Diels and Howard (2012)'s and Experiment PS2's settings since Experiment VIMS2 was designed as an extension of their study and our Experiment PS2.

Experimental Design

Seventeen combinations of r.m.s. velocity, frequency, and amplitude were used in this experiment (Table 5.1). Other details were similar to the Experiment VIMS1.

Table 5.1 The details of visual motion parameters (i.e., frequency, r.m.s. velocity, and amplitude) for the 17 conditions in the Experiment VIMS2

Cond #	Freq (Hz)	r.m.s. Vel (m/s)	Amp (m)	Cond #	Freq (Hz)	r.m.s. 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				

Procedures and Measurements

The procedures of this experiment were similar to the Experiment VIMS1, except that the participants were asked to continue to report their nausea ratings and complete the SSQ even after the exposure to the stimuli every five minutes and up to 15 minutes after the exposure. In other words, the recovery rates of VIMS symptoms severity right after the 30-min VIMS-provoking stimuli were also recorded.

5.4 Results

Results of the two VIMS experiments were presented in sequence for clarity.

5.4.1 Results of Experiment VIMS1

5.4.1.1 Nausea Ratings

The proportion of participants reaching different nausea ratings at each frequency condition was plotted in Figure 5.1. Larger proportions of participants for all levels of nausea ratings were found with all the moving visual stimuli conditions (0.05 Hz, 0.1 Hz, 0.2 Hz, and 0.8 Hz) compared to the static visual stimuli condition (0 Hz). While at 0.05 Hz more participants tended to report low severity of nausea (ratings of 1, 2, and 3), higher severity of nausea (ratings of 4, 5, and 6) were reported by larger proportion of participants at condition of 0.2 Hz.

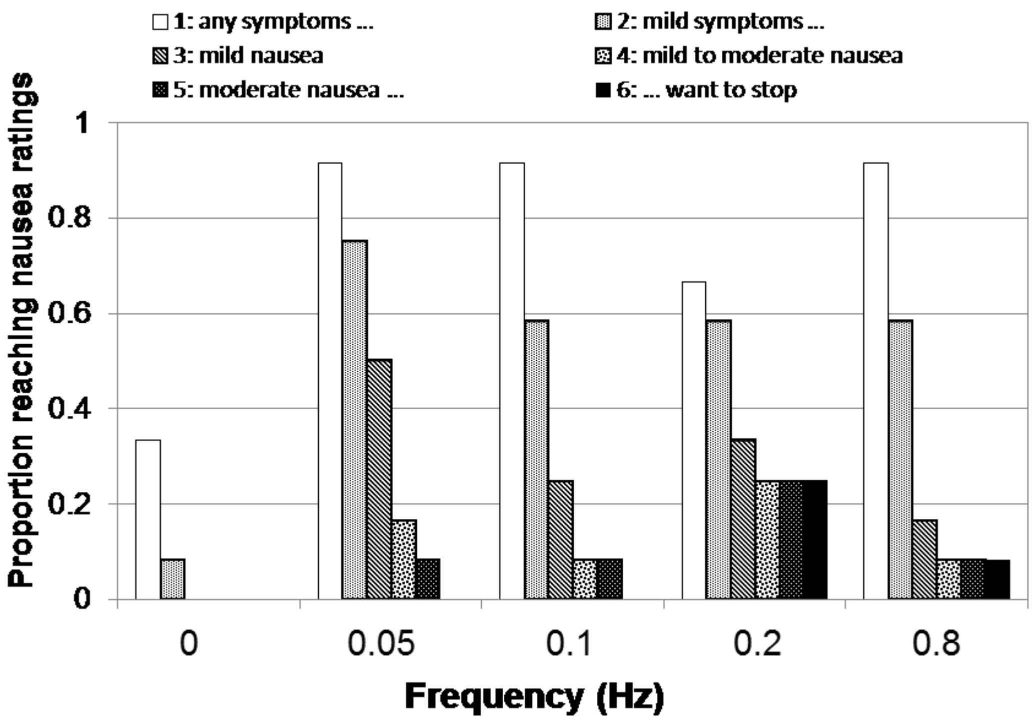


Figure 5.1 The proportion of participants reaching nausea ratings from 1 (any slight symptoms) through 6 (moderate nausea and want to stop) for all the five frequency conditions

The time courses of the average nausea ratings reported at a 5-min interval at each frequency of oscillation were shown in Figure 5.2. It was obvious that at any time after the start of the experiment the average nausea ratings of all moving conditions (0.05 Hz, 0.1 Hz, 0.2 Hz, and 0.8 Hz) were higher than the average nausea ratings of the static condition (0 Hz). Although not significantly different ($p>0.1$, Wilcoxon Signed Rank), the average nausea ratings at 0.2 Hz tended to be higher than other frequencies conditions at and after 10 min. This is interesting as Diels and Howarth (2012) reported that levels of VIMS peaked at 0.2 Hz.

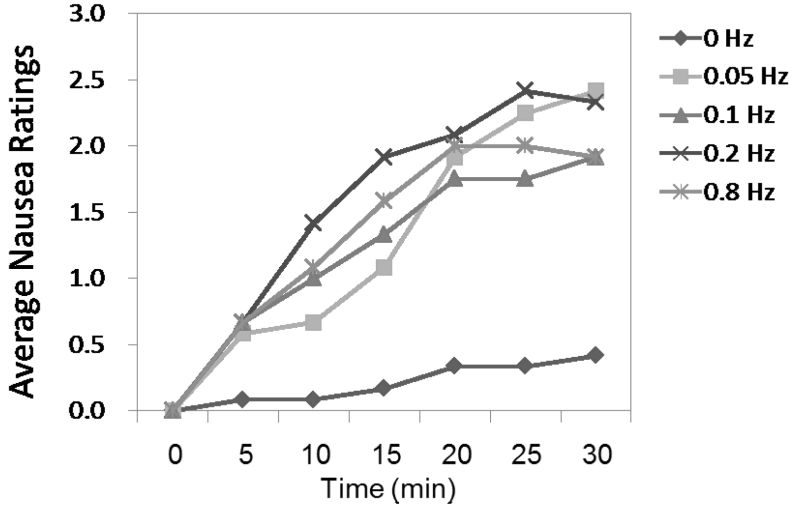


Figure 5.2 The time courses of the average nausea ratings reported by the participants at a 5-min interval at each frequency condition.

The average times to reach each level of nausea ratings were plotted against the frequencies (Figure 5.3). On average, excluding the 0 Hz condition, it took more than 10 min to reach the nausea rating of 1 (i.e., any unpleasant symptoms, however slight), around 20 min to reach the nausea rating of 2 (i.e., mild unpleasant symptoms, e.g. stomach awareness, sweating but no nausea), around 25 min to reach the nausea rating of 3 (i.e., mild nausea), and more than 25 min to reach any higher nausea ratings (i.e., above 3). Over all the conditions, significant effects of frequency were found using Friedman test on 'time to nausea rating of 1' and 'time to nausea rating of 2' (Chi-Square = 16.281, p=0.003; Chi-Square = 13.976, p=0.007; respectively). However, after excluding the control condition of 0 Hz, the effects of frequency were not significant (Friedman, p>0.9) for the time to reach any level of nausea ratings.

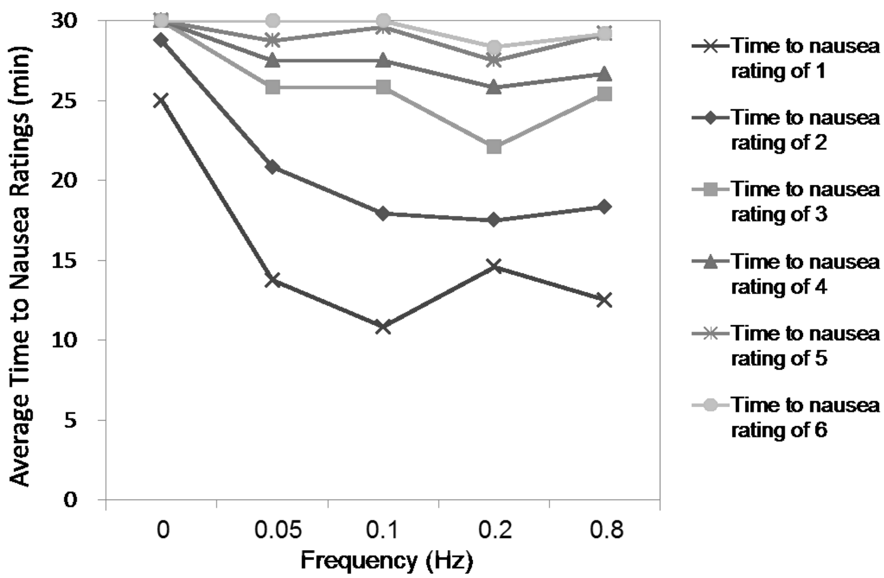


Figure 5.3 Frequency responses of the mean times to reach each level of nausea ratings.

The nausea ratings at 30 min and the accumulative nausea ratings of the participants are plotted in Figure 5.4. There was a significant effect of frequency on nausea ratings at 30 min among all the five conditions (0, 0.05, 0.1, 0.2 and 0.8 Hz; Friedman, Chi-Square = 18.307, p=0.001) as well as for the accumulative nausea ratings (Friedman, Chi-Square = 19.131, p=0.001). After excluding the control condition of 0 Hz, however, the effects of frequency were not significant in both cases (Friedman, p>0.3).

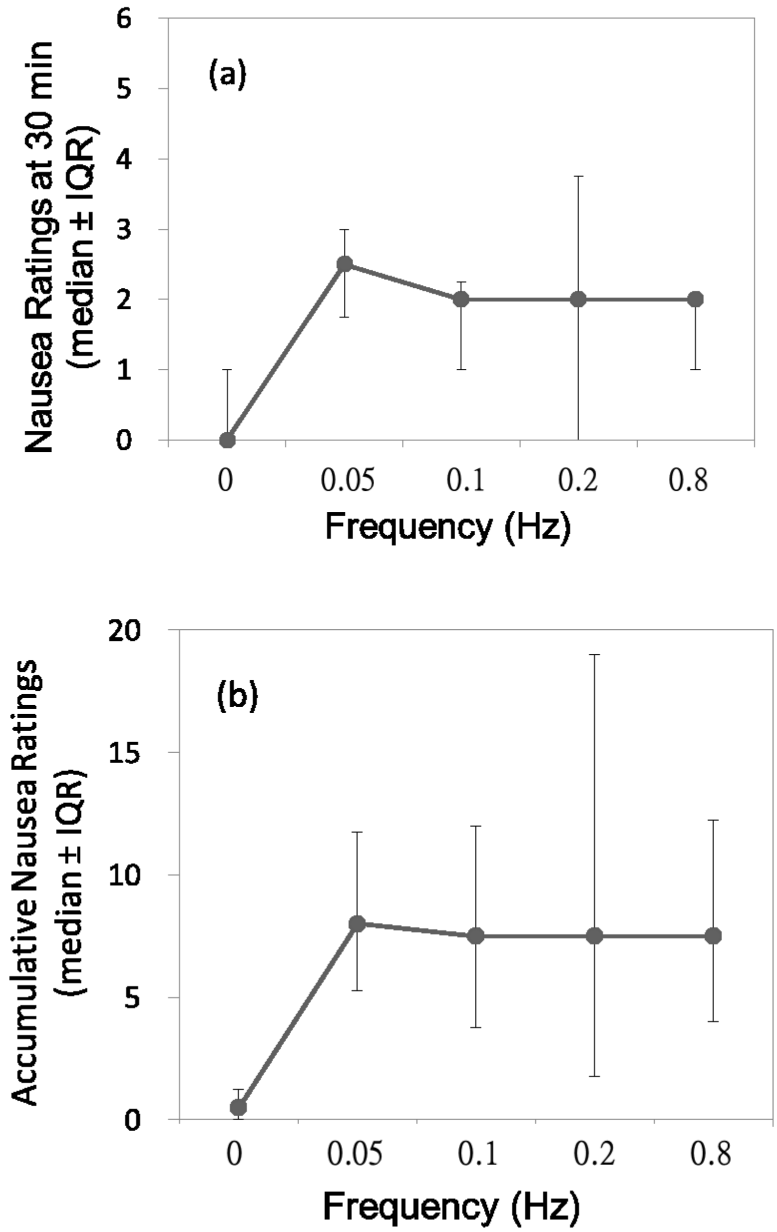


Figure 5.4 Frequency responses of (a) the nausea ratings at 30 min and (b) the accumulative nausea ratings of the participants. Median and inter-quartile range (IQR) were shown.

5.4.1.2 Simulator Sickness Questionnaire Scores

Results of Wilcoxon Signed Rank tests revealed that the SSQ total scores were significantly lower at 0 Hz than at 0.2 Hz (Z=-2.527, p=0.012), and 0.05 Hz (Z=-1.965, p=0.049). Nausea subscores were significantly lower at 0 Hz than at 0.8 Hz (Z=-2.410, p=0.016), and 0.05 Hz (Z=-2.489, p=0.013). No other significant results were found. In particular, there were no significant difference among 0.05 Hz, 0.1 Hz, 0.2 and 0.8 Hz for all the SSQ scores. The results of SSQ scores data are plotted in Figure 5.5.

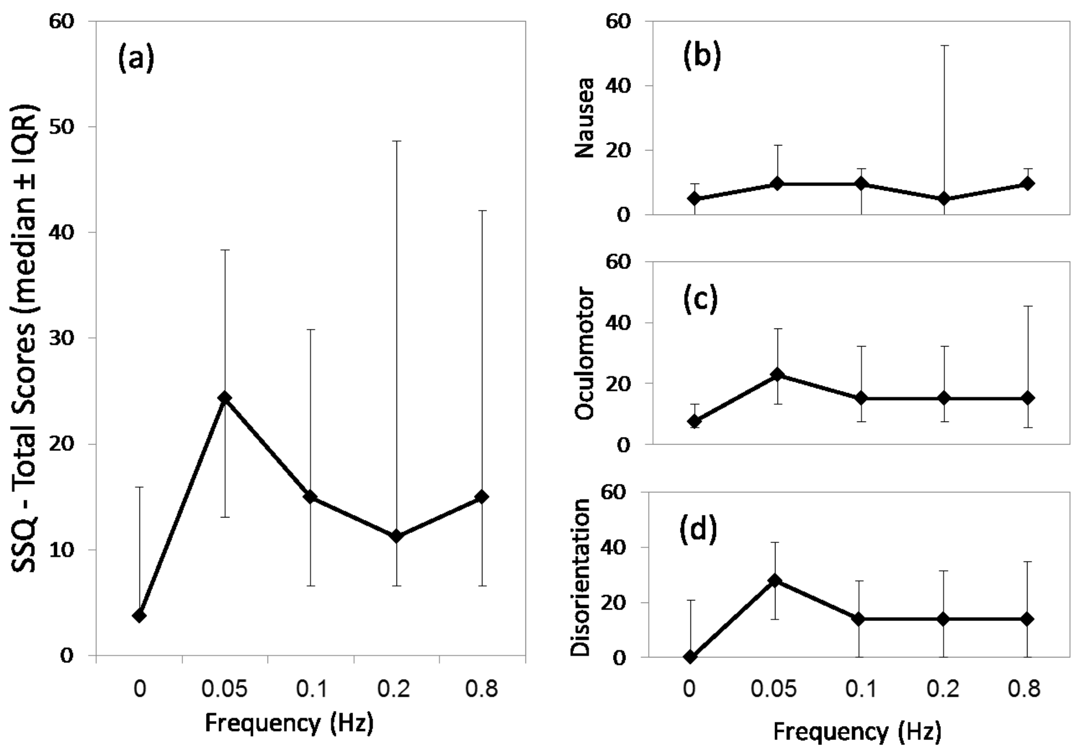


Figure 5.5 Frequency responses of the SSQ results (median with IQR). (a) Total SSQ scores; (b) Nausea subscores; (c) Oculomotor subscores; (d) Disoriention subscores.

The proportions of participants who reported an increase for each symptom (28 symptoms) in the SSQ at different levels of frequencies were plotted in Figure 5.6. The Cochran Q test was used to check if the symptoms reported in the SSQ were independent of the frequency. It was true that the proportions of participants who had an increase in symptoms were not dependent on the frequency ($p>0.1$) for all symptoms in the SSQ except for 'Drowsiness' ($p<0.05$). It is interesting to note that the levels of drowsiness peaked at 0.05 Hz – the frequency of visual motion proposed by Duh *et al.* (2004) to be the cause for the highest levels of VIMS.

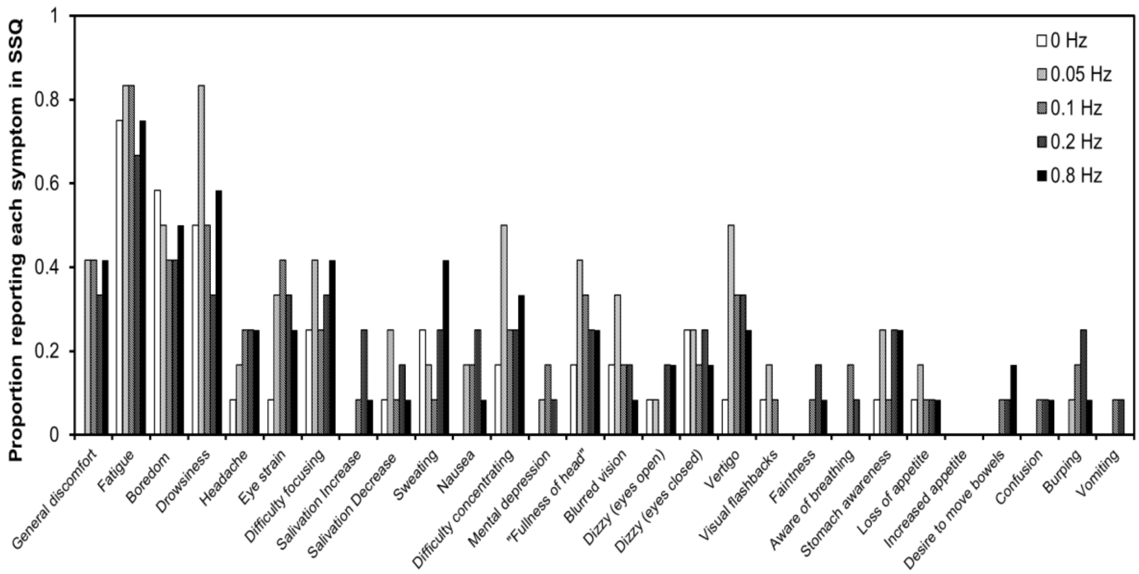


Figure 5.6 Proportion of the participants who reported an increase of severity at each symptom described in the SSQ for each frequency condition.

5.4.1.3 Vection Ratings

The time courses of the average vection ratings reported at 5-min interval at each frequency were shown in Figure 5.7. For moving conditions, at 5 min vection were similar (Friedman, Chi-square=2.469, p=0.481), but afterwards significantly less vection perception were reported by participants (p<0.05).

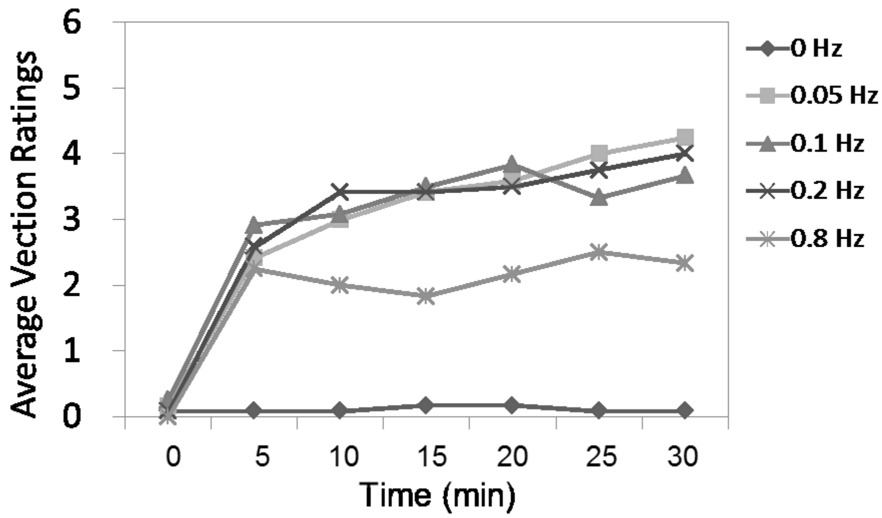


Figure 5.7 Time courses of the mean vection ratings of 12 participants for each frequency condition.

The effects of frequency were significant on both vection ratings at 30 min and the accumulative vection ratings (Friedman, Chi-Square = 31.284, p=0.000; Chi-Square = 29.339, p=0.000; respectively). After removing the control condition, the significant effects of frequency remained. In particular, vection ratings at 30 min 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). The accumulative vection ratings were also significantly lower at 0.8 Hz than at 0.2 Hz (Z=-2.005, p=0.045), 0.1 Hz (Z=-2.301, p=0.021), and 0.05 Hz (Z=-2.320, p=0.020). The vection ratings at 30 min and the accumulative vection ratings of the participants are plotted in Figure 5.8. The reduction of vection with increasing frequencies was consistent with the findings in both Experiments PS1 and PS2 for conditions with contant r.m.s. stimuli's velocities.

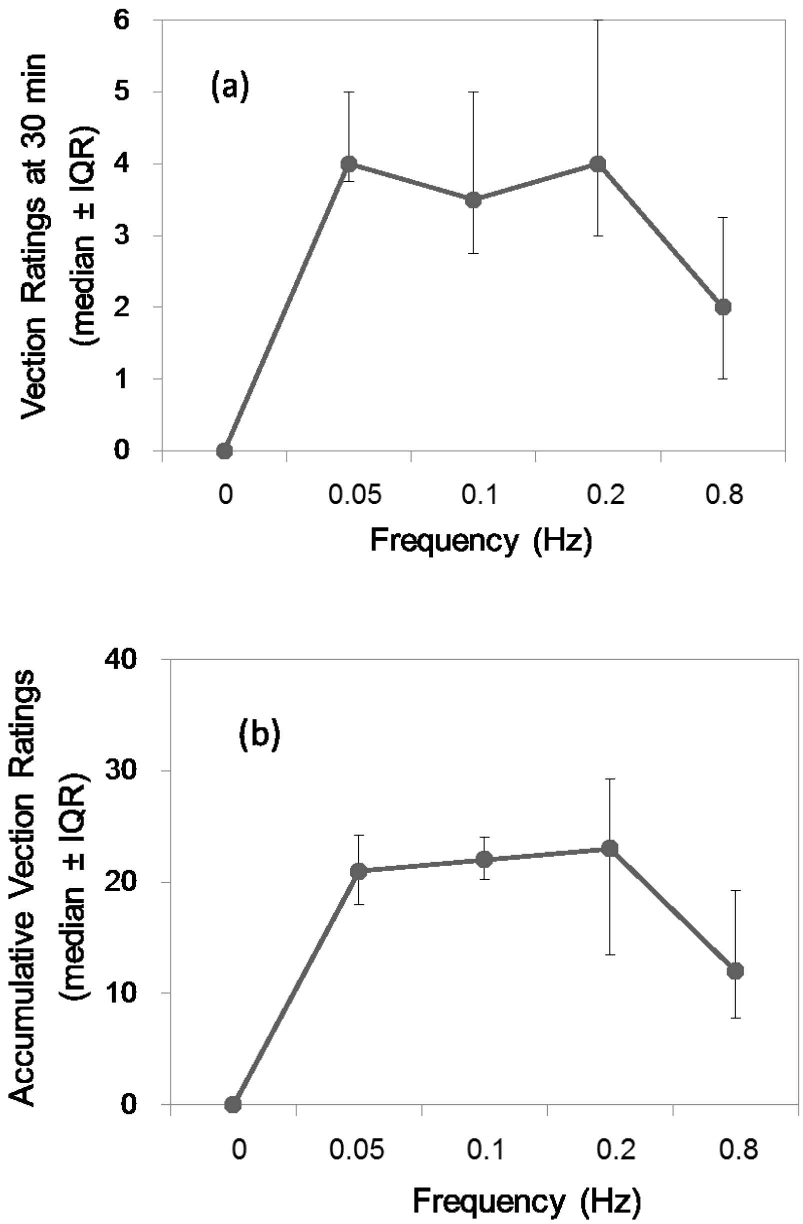
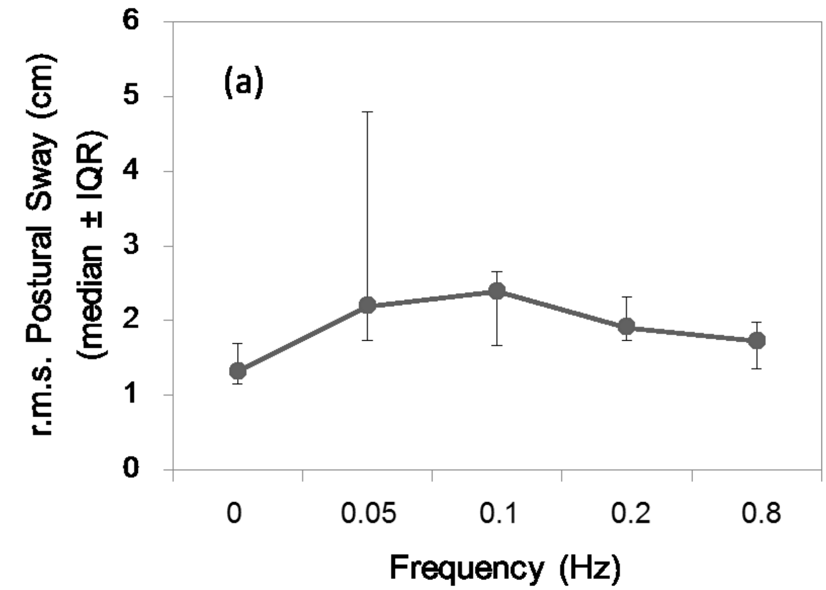


Figure 5.8 Frequency responses of (a) vection ratings at 30 min and (b) accumulative vection ratings. Median and IQR were shown.

5.4.1.4 Postural Sways

The r.m.s. postural sways over the entire 30-min exposure of 12 participants are plotted against frequency in Figure 5.9a, and were normalised by dividing the postural sways at the moving conditions (i.e., 0.05 ~ 0.8 Hz) by those at the static condition (0 Hz) for each participant to eliminate inter-subject variability (Figure 5.9b). For both the r.m.s. postural sways and the normalized r.m.s. postural sways, frequency had significant effects (Friedman, Chi-Square = 11.409, p=0.022; Chi-Square = 11.183, p=0.025; respectively). In particular, the r.m.s. postural sways at 0.8 Hz were significantly smaller than at 0.05 Hz (Z=-2.472, p=0.013) and 0.1 Hz (Z=-2.674, p=0.007). Similarly, the normalized r.m.s. postural sways at 0.8 Hz were significantly smaller than at 0.05 Hz (Z=-2.432, p=0.015) and 0.1 Hz (Z=-2.670, p=0.008). This suggests that the postural sway also followed a similar frequency response shape as that of vection. This is interesting as it is consistent with the postural instability theory proposed by Riccio and Stoffregen (1991).



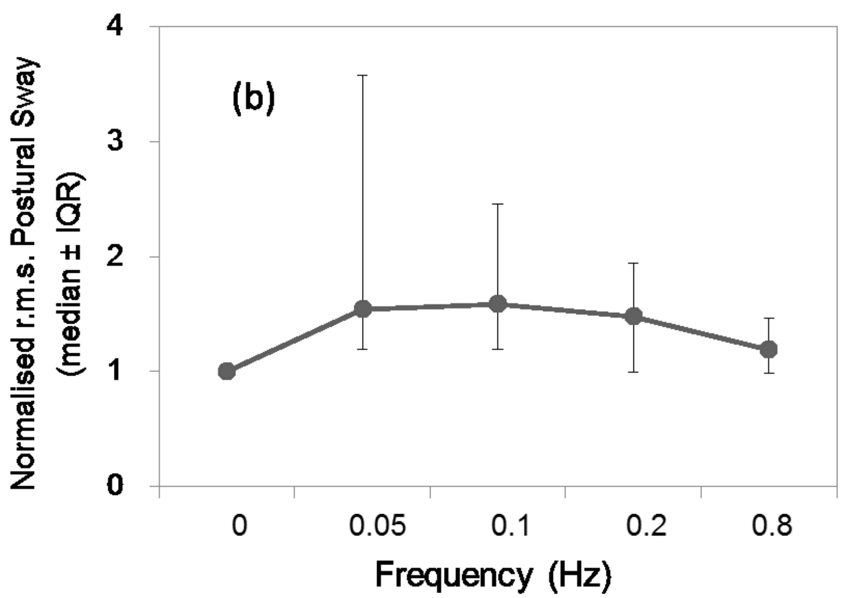


Figure 5.9 Frequency responses of (a) postural sway raw data and (b) normalized postural sway data.

5.4.2 Results of Experiment VIMS2

Results from the Experiment VIMS2 were organized in the following way: data were grouped into two categories based on how the frequencies of the visual stimuli were manipulated, namely (i) keeping r.m.s. velocity constant, or (ii) keeping amplitude constant.

5.4.2.1 Nausea Ratings

The time courses of the average nausea ratings of the thirteen participants at different frequencies levels were grouped into either with constant velocity or with constant amplitude in Figure 5.10. The duration from 0 to 30 min was the exposure duration of the visual stimuli, followed by a 15-min (the 30th to 45th min) recovery period. It was clear that nausea severity accumulated with time and peaked at the end of the stimuli (i.e., 30min), but dropped significantly at the first 5min after the cease of the exposure. This pattern was consistent in all conditions.

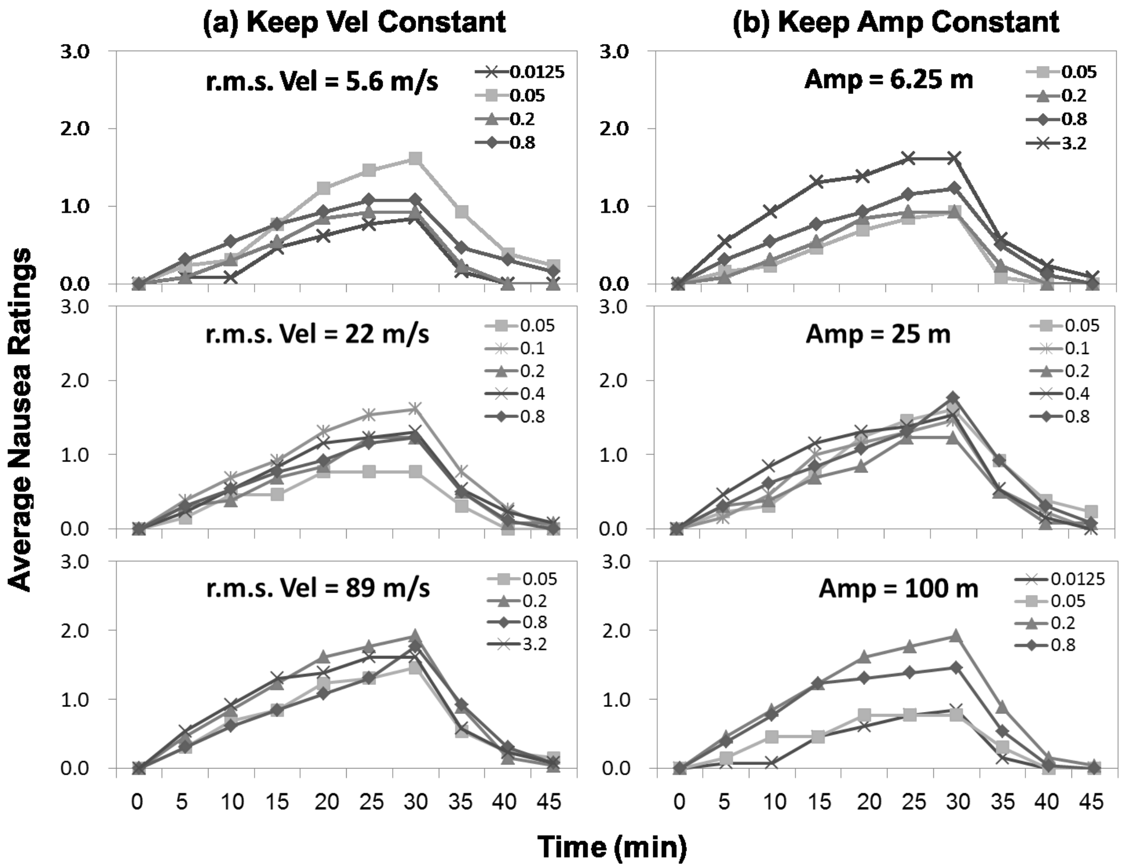


Figure 5.10 The time courses of the average nausea ratings of the thirteen participants viewing visual oscillations at various frequencies with (a) constant r.m.s. velocities at 5.6m/s, 22m/s, and 89m/s; or (b) constant amplitudes at 6.25m, 25m, and 100m.

The average time to reach the first three levels of nausea ratings were plotted against the frequencies (Figure 5.11). The participants reported nausea ratings of '1' (any symptom, however slight) and '2' (mild symptoms) significantly earlier exposed to visual stimuli with constant amplitude at 100 m when frequencies were higher (Friedman, Chi-square=10.963, p=0.012; Chi-square=14.077, p=0.003; respectively). This suggests that, with constant stimuli's amplitude, visual oscillations with higher frequencies were more provocative to the viewers in terms of causing sickness symptoms. However, the author admitted that the time taken to report sickness symptoms may not be the most sensitive measure (see the rest of this section).

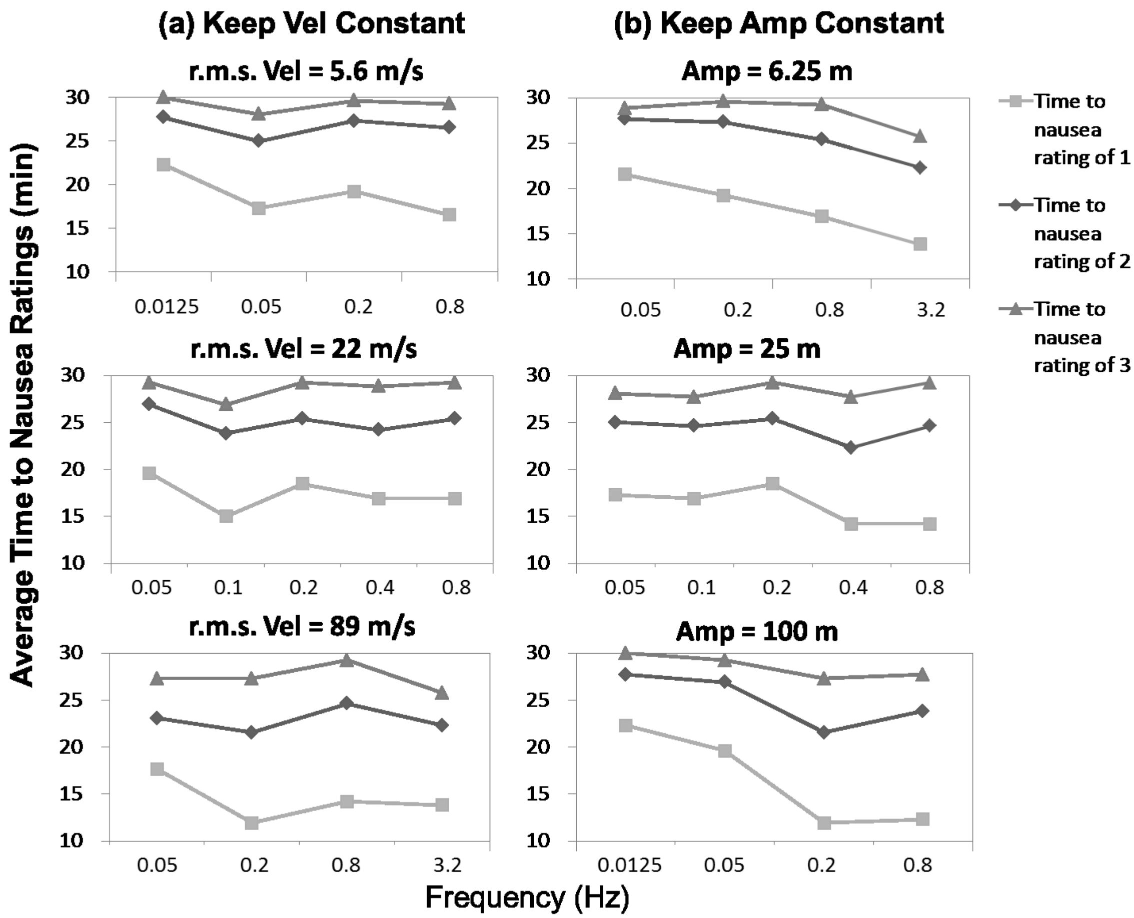


Figure 5.11 The average time to reach nausea level 1 (any slight symptoms; red line), nausea level 2 (mild symptoms; blue line), and nausea level 3 (mild nausea; green line) for the thirteen participants viewing visual oscillations at various frequencies with (a) constant r.m.s. velocities at 5.6m/s, 22m/s, and 89m/s; or (b) constant amplitudes at 6.25m, 25m, and 100m.

The proportion of participants reaching each level of nausea ratings was plotted in Figure 5.12. There was a significantly larger proportion of participants reported nausea ratings of 2 when exposed to visual stimuli at higher frequencies (3.2 Hz and 0.8 Hz) than at lower frequencies (0.2 Hz and 0.05 Hz) with constant amplitude at 6.25m (Cochran Q=13,, p=0.005), and with amplitude at 100m (Q=14.143, p=0.003).

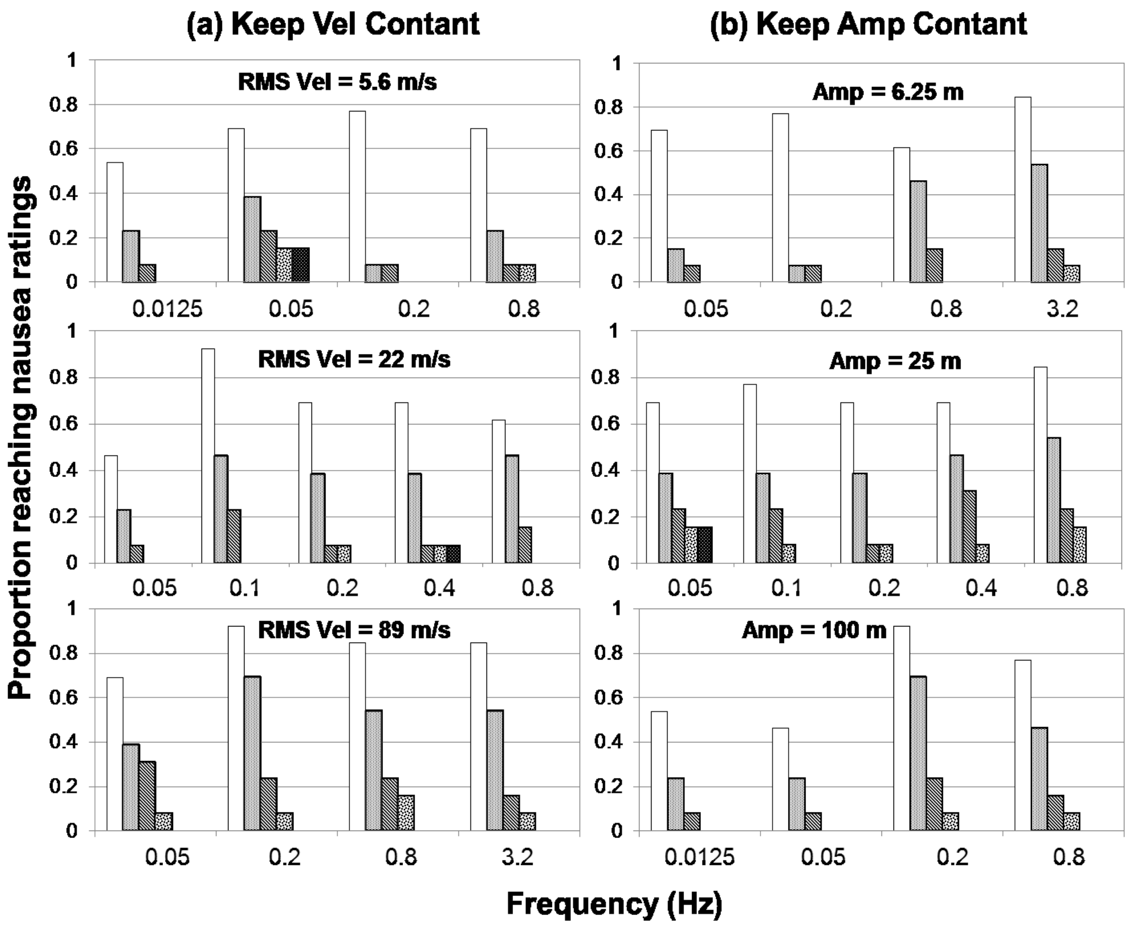


Figure 5.12 The proportion of participants reaching nausea ratings from 1 (any slight symptoms) through 6 (moderate nausea and want to stop) for all frequency conditions with (a) constant r.m.s. velocities at 5.6m/s, 22m/s, and 89m/s; or (b) constant amplitudes at 6.25m, 25m, and 100m.

The median nausea ratings (with IQR) at 30 min (i.e., the end of the exposure) were plotted for (a) keeping velocity constant and (b) keeping amplitude constant in Figure 5.13. Significant effects of frequency were found when keeping amplitude constant at 6.25 m and 100 m (Friedman, p=0.029 and p=0.000, respectively). When the stimuli's amplitude was 6.25m, levels of nausea increased with increasing frequency and the levels of VIMS was the significantly higher at 3.2 Hz (p=0.02, Wilcoxon). This trend is similar to the trend of increasing vection with increasing frequency reported in Experiments PS1 and PS2 when amplitude was kept constant. When the amplitude was at 100m, levels of VIMS were significantly higher at 0.2 Hz and 0.8 Hz. Although the absolute values of the frequencies at which the levels of VIMS were significantly higher were different, the data also followed the same overall trend – levels of VIMS increased with increasing frequencies. Inspections of Figure 5.13(b) also indicate that for the conditions with amplitude equals 100 m, VIMS reduced at 0.8 Hz after peaking at 0.2 Hz although the reduction was not significant.

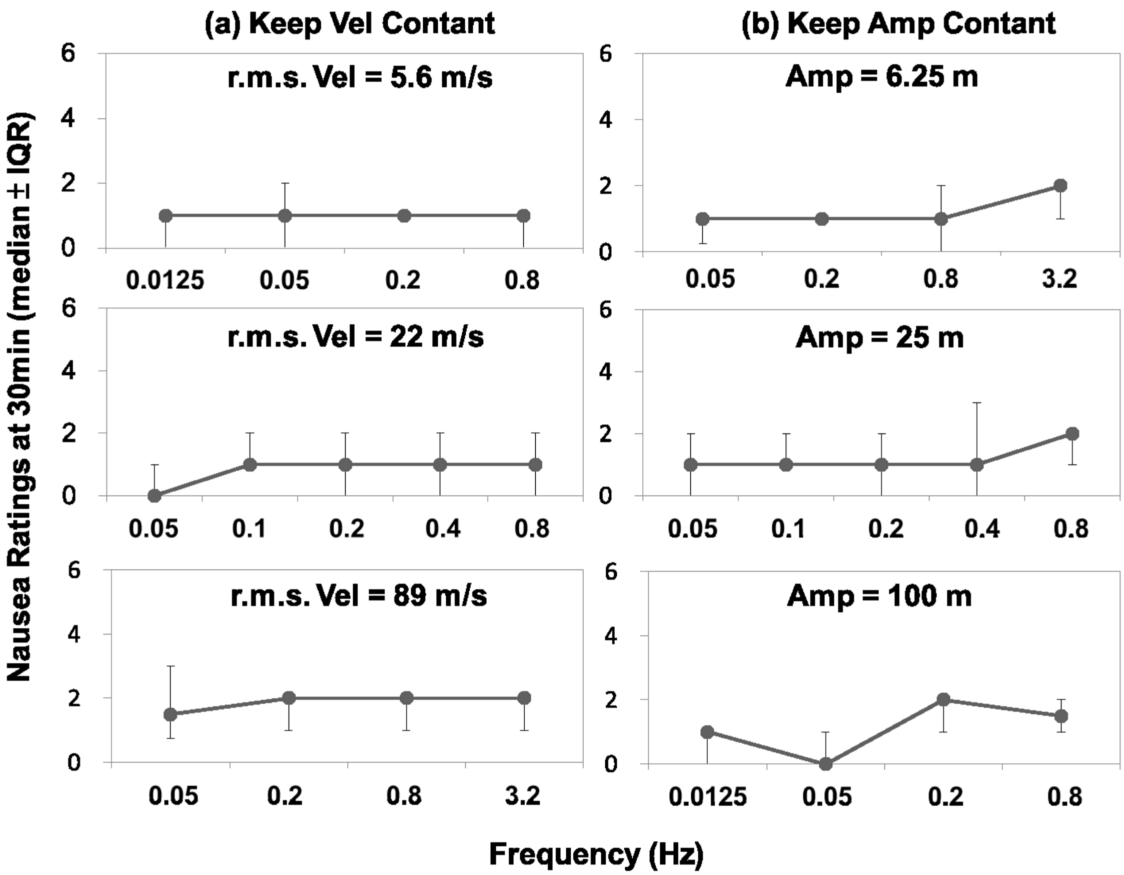


Figure 5.13 The frequency responses of the nausea ratings (median with IQR) for the thirteen participants viewing visual oscillations with (a) constant r.m.s. velocities at 5.6m/s, 22m/s, and 89m/s; or (b) constant amplitudes at 6.25m, 25m, and 100m.

5.4.2.2 Simulator Sickness Questionnaire Scores

The SSQ Total scores for (a) keeping velocity constant and (b) keeping amplitude constant were plotted in Figure 5.14. Frequency showed significant effects on the Total scores when keeping amplitude constant at 100m (Friedman, p=0.032). The sub-scores (Nausea, Oculomotor, and Disorientation) showed similar patterns as the Total scores (Figures were in Appendix 5.1 – 5.3).

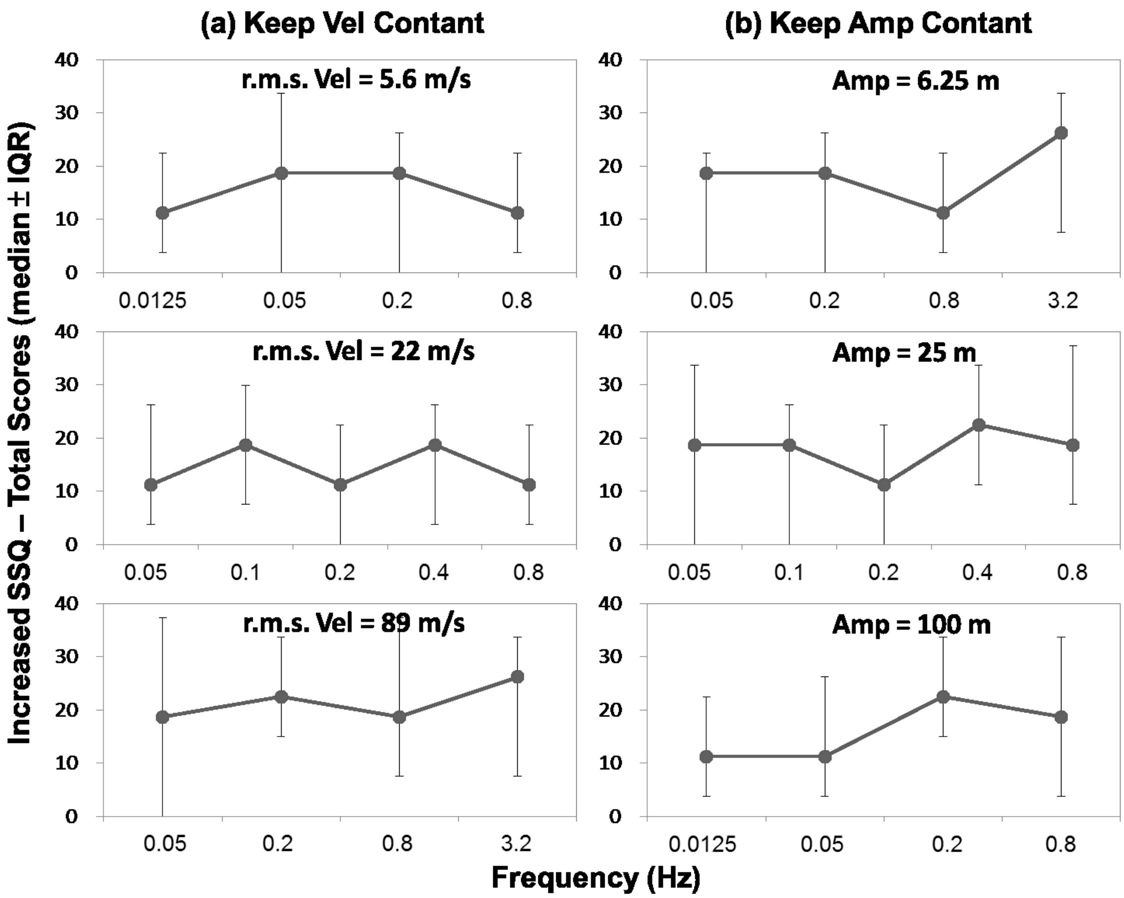


Figure 5.14 The frequency responses of the increased SSQ total scores for the 13 participants when viewing visual oscillation with keeping (a) r.m.s. velocities constant at 5.6m/s, 22m/s, and 89m/s; or (b) amplitudes constant at 6.25m, 25m, and 100m.

5.5 Discussion

5.5.1 Discussion of Experiment VIMS1

Postural sway and vection reduced significantly with increasing frequency when r.m.s. velocity was kept constant in Experiment VIMS1. However, VIMS did not significantly change with frequency. Results of this experiment contradicted both with Diels and Howard (2012) and Duh *et al.* (2004), but lend support to the spatial velocity (SV) hypothesis (So *et al.*, 2001a) that suggested VIMS should be similar among the viewers if the velocity of visual motion was kept constant. In Chapter 7, the data will be re-analyzed to extend the 'spatial velocity (SV)' methodology proposed in So *et al.* (2001a) to formulate a dose value to relate different stimuli strength to levels of nausea.

Frequency responses of postural disturbance and vection perception found in Experiment VIMS1 was similar to those reported in Duh *et al.* (2004). They both show characteristics of a low-pass filter. Nonetheless, frequency responses of VIMS are different from previous studies. Duh and his colleagues (2004) suggest that VIMS should peak at around 0.06 Hz while Diels and Howarth (2012) shows that VIMS is highest at around 0.2 Hz. In the current study, VIMS remains relatively constant across frequencies (no overall significant different) if r.m.s velocity was fixed. The fact that Duh's findings on postural sway and vection were duplicated in Experiment VIMS1 validated our experimental setup. Also, the possibility that our visual stimuli were not strong enough to cause VIMS was eliminated by the fact that nausea ratings significantly increased with exposure duration when the visual scenes were moving. So, what could have caused the differences among the three findings?

Further investigation revealed a large variance at 0.05 Hz for the normalized postural sways (see Figure 5.9). This indicated that for some participants their postural movements did not depend on frequency of the stimuli (Group 1 in Figure 5.15), but for others their postures were more unstable after watching the 0.05 Hz stimulus than stimuli at other frequencies (Group 2 in Figure 5.15). However, the levels of nausea reported at 30 min by the participants in Group 2 did not show a trend to peak at 0.05 Hz.

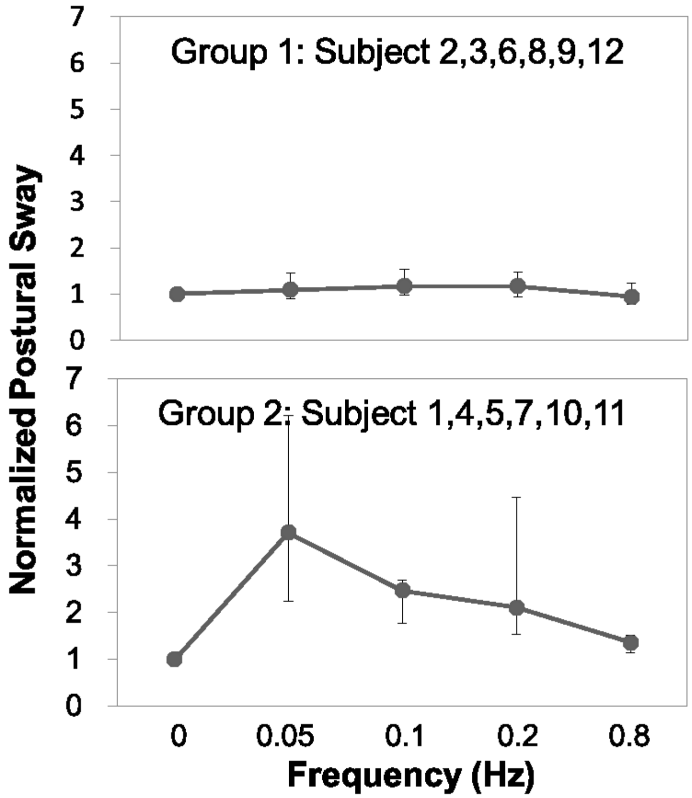


Figure 5.15 Grouping of the normalized postural sways. Participants in Group 1 had lower normalized postural sways at 0.05 Hz than those in Group 2.

Another large inter-variation was observed in the nausea data collected for stimuli at 0.2 Hz (see Figure 5.4a). Further inspections showed that some participants did report lower levels of nausea at 0.2 Hz than other frequencies (Group 1 in Figure 5.16), and some had similar levels of nausea regardless of frequency (Group 2), while others reported highest levels of nausea at 0.2 Hz (Group 3). Not surprising, when all three groups added together, no statistically significant results were found. In summary, subject bias might have caused the peaks reported in Diels and Howarth (2012). In this study, as both Experiments VIMS1 and VIMS2 confirmed the flat frequency responses of VIMS when the stimuli's velocity was kept constant, the findings should be generalizable. In Chapter 7, how the flat frequency response of VIMS is consistent with a theory proposed in So *et al.* (2001a) will be discussed.

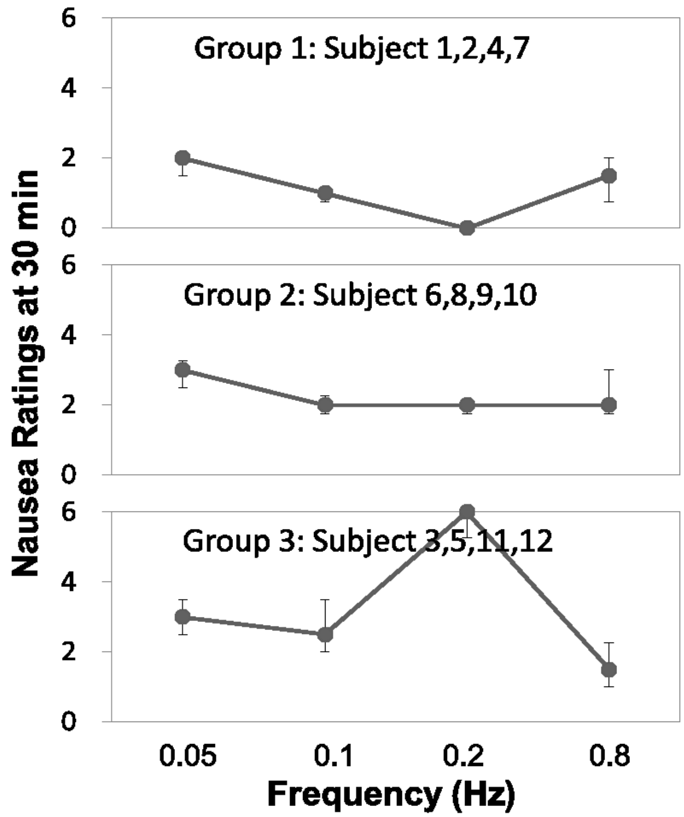


Figure 5.16 Grouping of the nausea ratings at 30 min. Participants in Group 1 had lowest nausea ratings at 0.05 Hz, Group 2 had the medium nausea ratings, and Group 3 had the highest nausea ratings.

5.5.2 Discussion of Experiment VIMS2

The Experiment VIME2 was the major experiment of this thesis since it examined the two-frequency-response hypothesis of VIMS directly. The results of nausea ratings and SSQ scores consistently showed that there were two types of frequency responses of VIMS. When the r.m.s. velocity was held constant (i.e., effects of amplitude were confounded with effects of frequency) VIMS had been at the similar levels across frequencies. However, when amplitude was held constant (i.e., effects of velocity were confounded with effects of frequency) VIMS tended to increase with increasing frequency. It is worth noting that this increasing trend with increasing frequencies were also reported in rated vection collected in Experiments PS1 and PS2 when the amplitudes of the stimuli were kept constant.

Although the current study purposely used the same stimuli and the same experimental setups as Diels and Howard (2012), the results contradict their findings. Diels and Howard (2012) combined results from two different experiments with different participants. There was a chance that their findings were biased by individual preference for oscillation frequency as explained in the above section. In this study, the findings of a flat frequency response in Experiment VIMS2 are consistent with findings of Experiments VIMS1, PS1 and PS2 when the stimuli's velocities were kept constant.

A comparison of our findings with the hypothetical theory proposed in So *et al.* (2001a) indicated that they are consistent. The 'spatial velocity (SV)' hypothesis proposed in So *et al.* (2001a) predicts two situations of VIMS severity: (i) if viewers are exposed to visual oscillations with similar velocity; similar scene content; and for similar duration, they would report similar levels of VIMS, or (ii) if viewers are exposed to visual oscillations with similar amplitude but different velocities, they would report different levels of VIMS as a function of the velocity. The first hypothetical situation can be supported by the flat frequency responses of VIMS reported in Experiment VIMS1 and in Experiment VIMS2 for conditions with constant velocity. For the second hypothetical situation, it can be supported by the increasing frequency responses of VIMS reported in Experiment VIMS2. More specifically, results from the Experiment VIMS1 indicated that when the stimuli were moving at constant velocity, the levels of VIMS remained similar within the range of 0.05 Hz to 0.8 Hz. Hence, supporting the first hypothetical situation. When the stimuli's amplitudes are held constant as in Experiment VIMS2, the levels of VIMS increased when the stimuli's frequency increased from 0.0125 Hz to 3.2 Hz. Hence, supporting the second hypothetical situation. This result partially agrees with Chen (2006). In Chen's study, the amplitude of the stimuli was also kept constant. More discussion on how the current finding fits into the existing body of literature can be found in Chapter 7.

Although the results of Experiments VIMS1 and VIMS2 reported two different frequency responses (one flat and one increasing with increasing frequency) and support the two-frequency-response hypothesis, within the frequency range of 0.05 Hz to 0.8 Hz, VIMS was not dependent on frequency regardless of whether the velocity or the amplitude of the stimuli were kept constant. This suggests that there exists a range of stimuli frequency that the two frequency responses converge to one. Further work to verify this is desirable.

In addition to the findings about the two distinctively different trends for frequency responses when stimuli velocity or stimuli amplitude was kept constant, it is interesting to compare the frequencies of stimuli at which the levels of VIMS were significantly higher among conditions in this study as well as from those reported in the literature (see Chapter 2). As explained in Chapter 2, two clusters of findings have reported that watching visual oscillations at 0.06 Hz or 0.2 to 0.4 Hz would results in highest levels of VIMS. In this study, we have data indicating that when the velocity of visual oscillation was held constant, changes of oscillation frequency between 0.0125Hz to 0.8Hz and changing the frequency from 0.05Hz to 3.2 Hz did not significantly affect levels of VIMS. However, when amplitude of oscillations was held constant at 6.25 meters, levels of VIMS increased significantly with increasing frequencies and were the highest at 3.2 Hz. When the amplitude was held constant at 100 meters, levels of VIMS also increased significantly with increasing frequency and levels of VIMS were the highest at 0.2 Hz and 0.8 Hz. A reasonable conclusion would be that the frequency responses of VIMS cannot be interpreted alone without the explicit considerations of the velocity and the amplitude of the visual oscillations. In Chapter 6, a way to plot the frequency responses as functions of velocity, amplitude as well as frequency is proposed and discussed.

5.6 Conclusions

When stimuli's velocity was kept constant, a flat frequency response of VIMS was reported. When stimuli's amplitude was kept constant, levels of VIMS increased when frequency increased from 0.0125 Hz to 0.8Hz and from 0.05Hz to 3.2Hz. This finding supports the two-frequency-response hypothesis which predicts two types of frequency responses for level of VIMS. Since keeping stimuli velocity or keeping stimuli amplitude constant clearly affects the frequency responses of VIMS, just plotting levels of VIMS against frequencies may not be the best way to visualize the frequency plots. In Chapter 6, a new way to visualize a frequency response of VIMS is proposed.

The flat frequency response of VIMS contradicts the previous finding by Diels and Howarth (2012) which predicts that visual oscillation at 0.2 Hz would produce higher levels of VIMS than visual oscillations at other frequencies. Evidence for larger inter-subject variability was founded for VIMS provoked by 0.2Hz visual oscillation and this could be a possible reason for the disagreement between this study and Diels and Howarth (2012).

The flat frequency response of VIMS also contradicts with the findings in Duh *et al.* (2004) which predicts that visual oscillations at 0.06Hz will provoke higher levels of VIMS than stimuli at other frequencies. However, significantly larger postural sway was reported with visual oscillations at 0.05Hz. Further work to investigate the relationships among the frequency responses of postural sway and VIMS may be fruitful.

The findings of Experiments VIMS1 and VIMS2 supports a ‘spatial velocity (SV)’ hypothesis previously reported in So *et al.* (2001a). In Chapter 7, data collected in the Experiments VIMS1 and VIMS2 will be re-analyzed according to the SV hypothesis to develop a dose value formulae to relate levels of VIMS to velocity of the visual oscillations.

CHAPTER 6: STANDARDIZATION OF THE FREQUENCY RESPONSES OF VISUALLY INDUCED MOTION SICKNESS AND VECTION

SUMMARY

ISO (IWA 3:2005) urged for the standardization of VIMS. In previous chapters, two types of frequency-responses of VIMS as well as vection perception had been identified. In the light of the findings, the previous way to plot levels of VIMS or vection against frequencies are not adequate and effective in presenting the frequency responses. This chapter presents a unified and simple form of visualization method to present the two types of frequency responses on a single graph. This thesis urges the research community on VIMS to use this new way of presentation so that readers would be able to tell the effects of velocity and / or amplitude easily. Using this new method of plotting, the effects of stimuli's velocity and stimuli's amplitude will be shown explicitly on the figure.

6.1 Introduction

In Chapters 4 and 5, two types of frequency responses of VIMS and vection have been identified with two types of visual scenes (radial stripes and star field) oscillation along the fore-and-aft axis at different combinations of motion variables (e.g., frequency, velocity, and amplitude). Results indicate that the frequency responses of VIMS and vection cannot be interpreted correctly unless both the amplitudes and velocities of the visual oscillations are known. Consequently, the chapter presents a new way of plotting the frequency responses with explicit information on both the amplitude and velocity of the visual stimuli. Data collected in this study will also be presented afresh using the new graphical methods.

Apart from academic consideration, an accurate and simple way to visualize how the levels of VIMS and vection will change with the frequency, amplitude and velocity of the visual oscillations can help game developers or designers of immersive virtual reality applications to optimize their designs so that they identify and determine the optimized combinations of stimuli's velocity and amplitudes to provide experience of thrill through maximizing the sensation of vection as well as minimize the chances of causing high levels of VIMS. Riecke (2010) has reported that a strong sense of vection among users is usually associated with improved user experience in immersive VR applications. On the other hand, suffering from symptoms of VIMS will definitely lower the general acceptance of VR technology. The author sincerely hope that the new way to visualize the relationships among VIMS, vection and the velocity and amplitude of visual stimuli can provide guidance for display/game designers in the pursuit of provoking high levels vection without symptoms of VIMS.

Frequency responses of human perception have been utilized, standardized, and commercialized in various fields of industry (e.g., discomfort caused by physical vibration in British Standard Institution [BS] 6841 1987; International Organization of Standardization [ISO] 2631-1 1997). The new methodology to visualize the frequency responses of VIMS and vection presented in this chapter are consistent with those in BS 6841 1987 (Griffin, 1998).

6.2 Visualization of multiple frequency responses of Vection

6.2.1 Frequency responses of vection: 3D plots

Median vection data collected in Experiments PS1 are plotted as a 3D figure in Figure 6.1 as functions of stimuli's velocity and stimuli's frequency (Figure 6.1a) or as functions of stimuli's amplitude and stimuli's frequency (Figure 6.1b). This is the most straightforward way to visualize the two types of frequency responses of vection collected in Experiment PS1. From the perspective of a game or VR application designers, it may be better to replot Figure 6.1 as functions of stimuli's velocity and stimuli's amplitude because these two parameters can easily be manipulated (Figure 6.2). However, while both Figures 6.1 and 6.2 represent faithfully the data collected, the figures do not make use of the data trends to predict what will happen for a condition beyond what has been studied.

A review of literature indicates that percentage likelihood graphs have been used to illustrate and present human vibration perception threshold (Griffin, 1990; Kwok *et al*., 2009). In the next section, the 50% likelihood of vection perception will be constructed.

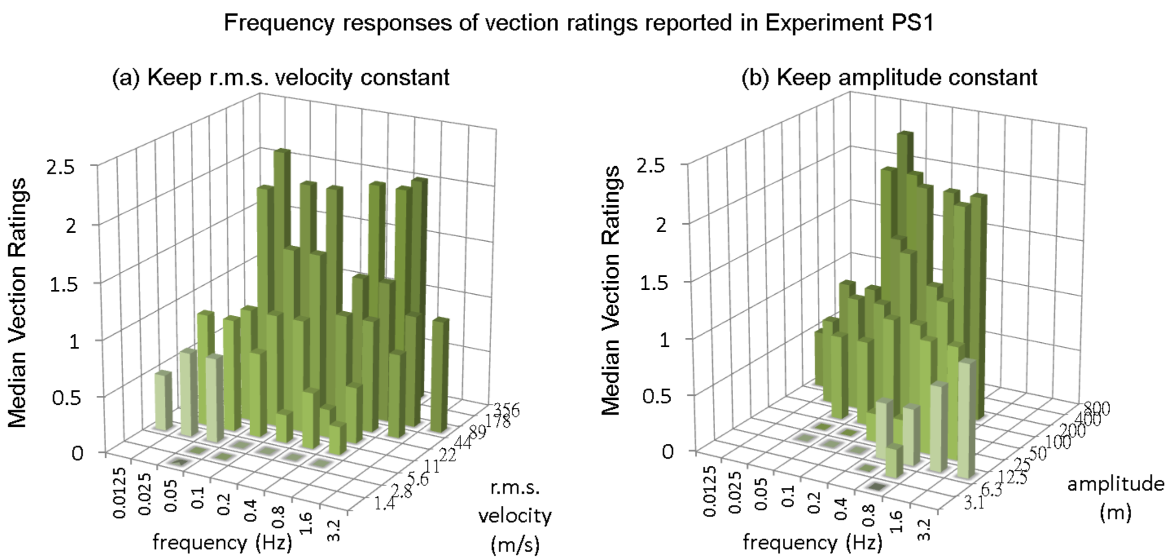


Figure 6.1 Frequency responses of median vection as (a) keeping stimuli's r.m.s. velocity constant and (b) keeping stimuli's amplitude constant.

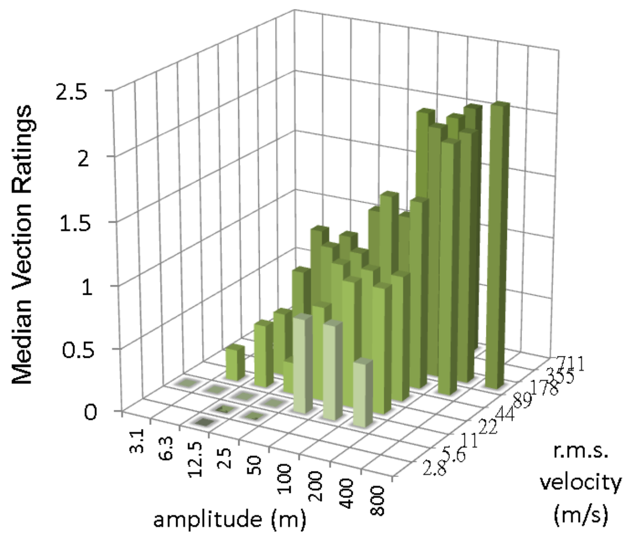


Figure 6.2 Median vection as functions of stimuli's velocity and stimuli's amplitude.

6.2.2 Percentage likelihood graphs of vection perception

6.2.2.1 Calculation of the 50% likelihood graph for vection

In order to construct a unified frequency response graph that can predict, I propose to adopt the likelihood curves for vection perception (Figure 6.3). This idea is borrowed from studies of vibration perception threshold (Griffin, 1990; Kwok *et al.*, 2009). Vibration perception thresholds are plotted as functions of acceleration and frequency of the vibration because human vestibular systems are sensitive to the acceleration levels of vibration (Highstein *et al.*, 2004). In this case, vection is induced by perceiving visual motion and evidence shows that our visual systems are sensitive to velocity of visual motion (Schrater *et al.*, 2000). Therefore, the likelihood curves for vection are plotted as functions of velocity and frequency. In addition, contours of constant levels of stimuli's amplitude are embedded diagonally for the ease of identifying and locating specific values of amplitude in relation to particular vection levels.

We have chosen 50% likelihood as the benchmark. Theoretically, any percentage of likelihood can be used. Please note that the measurement of vection was not a forced choice between with and without vection and participants could readily report zero vection (i.e., no vection at all) during the experiment. Indeed, this occurred very often in as shown in Figure 6.3, there are four 50% likelihood curves and regions coloured in red, blue, green and yellow representing combinations of stimuli parameters that has caused 50% of the participants in Experiment PS1 to experience strong, medium, slight vection, and no vection respectively. Inspections of the figure indicate that the choice of 50% include a good spread of different levels of reported vection from none to strong. Data of vection from the Experiment PS1 (indicated inside the dotted black box in Figure 6.3) were used to fit these likelihood curves since it contained the largest body of vection data within one single experiment.

The 50% likelihood curves of vection were calculated as follows: Firstly, the proportion of participants that perceived and reached a particular level of vection or higher was calculated for each condition in Experiment PS1. Secondly, the % proportions were regressed over the natural logarithms of r.m.s. velocities under each frequency which has more than two conditions. The regression details are summarized in Table 6.1. Thirdly, after the fitted equations were derived, the fitted values of r.m.s. velocities for the 50% likelihood of that particular level of vection perception was read off the regression fitted line (see Table 6.1). Finally, all the fitted values of r.m.s. velocities were connected and plotted as Figure 6.3. As you can read from Table 6.1, all regression equations had very good fits.

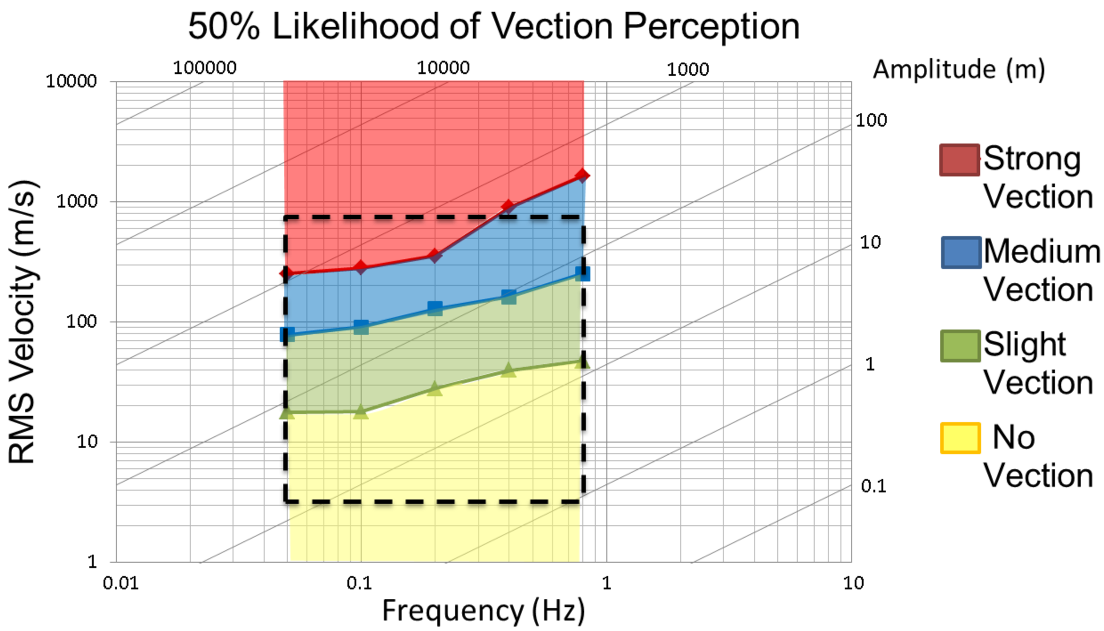


Figure 6.3 The 50% likelihood of vection perception plotted against r.m.s. velocity v.s. frequency (with diagonal axis of amplitude). Four levels of vection perception (no vection in yellow; slight in green; medium in blue; strong in red) were interpolated in different areas of r.m.s. velocities and frequencies. Dotted black box contained experimental data from Experiment PS1.

Table 6.1 Details of fits of a log-linear regression line with the % of participants reaching a certain level of vection (first column) as the 'Y' variable and the stimuli's velocities as the 'X' variables. Data are grouped according to the frequency of visual oscillations (second column). Depending on the frequency, number of data points for each regression analyses ranged from 5 to 7 (hence degrees of freedom, DOF, ranged from 4 to 6).

Regression Results of 50% Likelihood of Vection Perception						
	Freq(Hz)	DOF	R-square	Coefficient	Intercept (@1m/s)	Estimated velocity for 50% likelihood
Slight Vection	0.05	6	0.9187	0.1597	0.0404	17.777
	0.1	5	0.9605	0.1772	-0.011	17.881
	0.2	4	0.9375	0.2164	-0.221	27.988
	0.4	5	0.8993	0.2329	-0.3559	39.447
	0.8	6	0.9337	0.1803	-0.1949	47.188
Medium Vection	0.05[a]	5	0.9034	0.2288	-0.497	78.063
	0.1[a]	4	0.9723	0.2669	-0.7026	90.541
	0.2[a]	3	0.9917	0.2958	-0.9371	128.812
	0.4[a]	4	0.9587	0.2669	-0.8576	161.830
	0.8[a]	5	0.9548	0.2391	-0.8223	252.225
Strong Vection	0.05[b]	3	0.9783	0.2164	-0.696	251.339
	0.1[b]	2	0.9231	0.2885	-1.128	282.303
	0.2[b]	1	1	0.3607	-1.6184	355.322
	0.4[b]	2	1	0.2164	-0.971	895.692
	0.8[b]	3	0.9931	0.1731	-0.7818	1644.133

[a] DOF reduced by one because one data point at the lowest velocity has been removed through piece-wise linear approach (see Section 6.2.2).

[b] DOF reduced due to piece-wise linear regressions (see Section 6.2.2).

The likelihood curves of vection have unified the results from the two different frequency responses of vection. As shown in Figure 6.3, for the same levels of r.m.s. velocity, higher frequencies associate with lower levels of preceived vection; while for the same levels of amplitdue, higher frequencies are clearly associate with higher levels of preceived vection. The intepretation of this graph is exactly in line with the findings of the two-frequency-resposnes for vection but in a much concise and clear form (see Chapter 4).

6.2.2.2 Piece-wise linear regressions

For medium vection, the data associated with the lowest velocity were 0%. Inspections of the raw regression plot (see an example in Figure 6.4), it appears that there is a threshold of velocity below which no participants would report vection. Consequently, we applied a piece-wise linear approach (log-linear, in fact, Figure 6.3) and only focus on the remaining data point (i.e., the second piece of the regression plot).

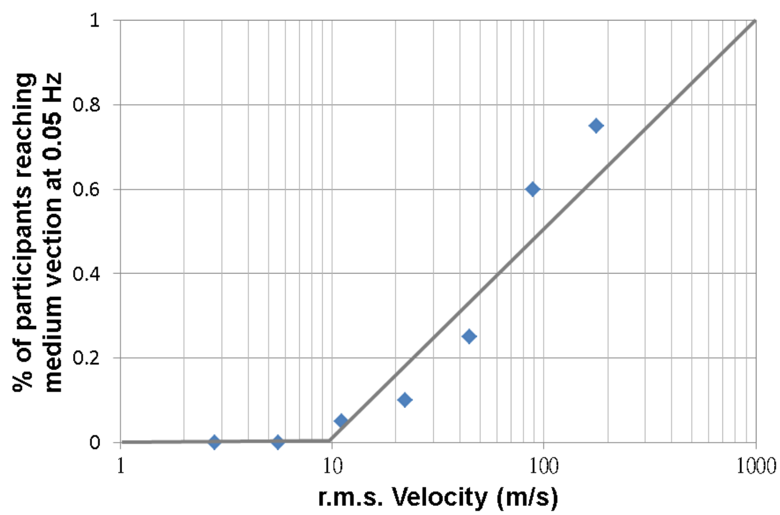


Figure 6.4 An example regression plot of % of participants who reported medium vection as functions of stimuli's velocity.

Similarly, for strong vection, inspections of the raw regression plots indicated a velocity threshold below which none of the participants reported strong vection (see Figure 6.5). Again, the regression analyses as shown in Table 6.1 focused on the second (higher velocity) pieces of linear regression. The concept of piece-wise linear analyses also allows the exclusion of the origin (i.e., 0% at zero velocity) in the regression analyses as shown in Table 1.

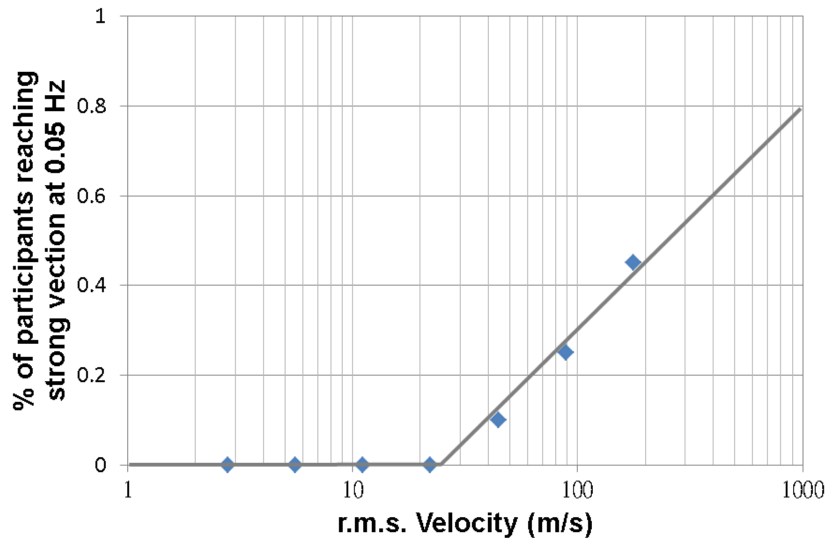


Figure 6.5 An example regression plot of % of participants who reported strong vection as functions of stimuli's velocity.

6.3 Visualization of multiple frequency responses of VIMS

6.3.1 Frequency responses of nausea: 3D plots

Median nausea data collected in Experiments VIMS2 are plotted as a 3D figure in Figure 6.6 as functions of stimuli's velocity and stimuli's frequency (Figure 6.6a) or as functions of stimuli's amplitude and stimuli's frequency (Figure 6.6b). This is the most straightforward way to visualize the two types of frequency responses of nausea ratings collected in Experiment VIMS2. From the perspective of a game or VR application designers, it may be better to redraw Figure 6.6 as functions of stimuli's velocity and stimuli's amplitude because these two parameters can easily be manipulated (Figure 6.7). Similar to Figures 6.1 and 6.2, Figures 6.6 and 6.7 do not make use of the data trends to predict what will happen for a condition beyond what has been studied. Consequently, the 50% likelihood of nausea will be constructed in the next section.

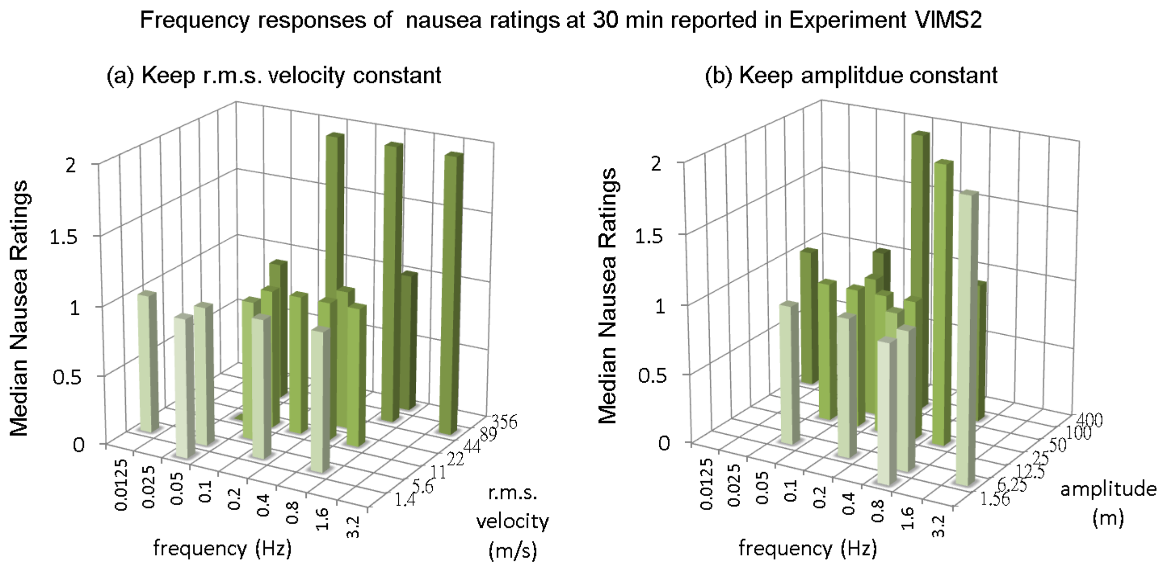


Figure 6.6 Frequency responses of median nausea as (a) keeping stimuli's r.m.s. velocity constant and (b) keeping stimuli's amplitude constant.

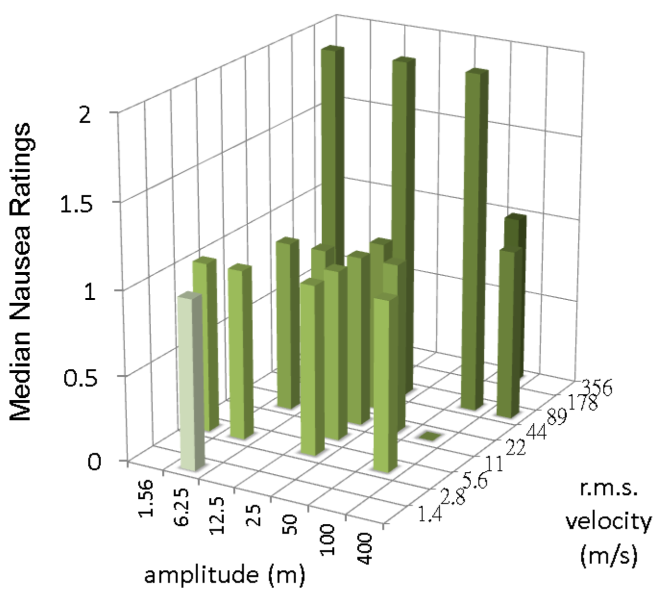


Figure 6.7 Median nausea as functions of stimuli's velocity and stimuli's amplitude.

6.3.2 Percentage likelihood graphs of nausea

6.3.2.1 Calculation of the 50% likelihood graph for nausea

Similar to vection, the 50% likelihood curves of nausea have been constructed (Figure 6.8). Data of nausea ratings at 30 min from the Experiment VIMS2 were extracted and used to construct the 50% likelihood curves for VIMS. Since there were few incidences of high-level nausea ratings (e.g., nausea ratings above 3) among participants in the Experiment VIMS2, only likelihood curves of nausea levels from 0 to 3 (0: "No symptom"; 1: "Any slight symptoms"; 2: "Mild symptoms"; 3: "Mild nausea") are calculated. The calculation procedure was similar to those of vection. The regression details are summarized in Table 6.2. A comparison between Tables 6.1 and 6.2 indicates that the levels of fit as measured by R-square values are much lower with VIMS data. One possible reason is that the number of data points available for each regression analyses as shown in Table 6.2 was much less than those in Table 6.1. As a result, a single data point deviation could cause a large reduction of R-square value (see Figure 6.9). A further investigation of the raw data of Figure 6.9 indicated that 3 more participants reported 'no symptom' at 22 m/s than other three velocities and there was no irregularity with these data. I acknowledge that the low R-square for the regression analyses for 0.05 Hz and 'any slight symptoms' is unacceptably low. Therefore, this regression line was rejected. A more reasonable estimate for the velocity associated with the 50% likelihood of "Any slight symptoms" was made as "1.56 m/s" (marked as black on Figure 6.8) since from Figure 6.9 the author observed that the overall % was above 50% and "1.56 m/s" was the lowest velocity had been studied, above which it was assumed that at least 50% of participants experienced "any slight symptoms". As a result, prediction under the 50% likelihood curve for "any slight symptoms" between 0.05 Hz to 0.2 Hz was unknown (the grey area in Figure 6.8). In other words, the real data points were used to make a 'safe' estimate for the velocity associated with the 50% likelihood of "Any slight symptoms" when frequency equals 0.05 Hz.

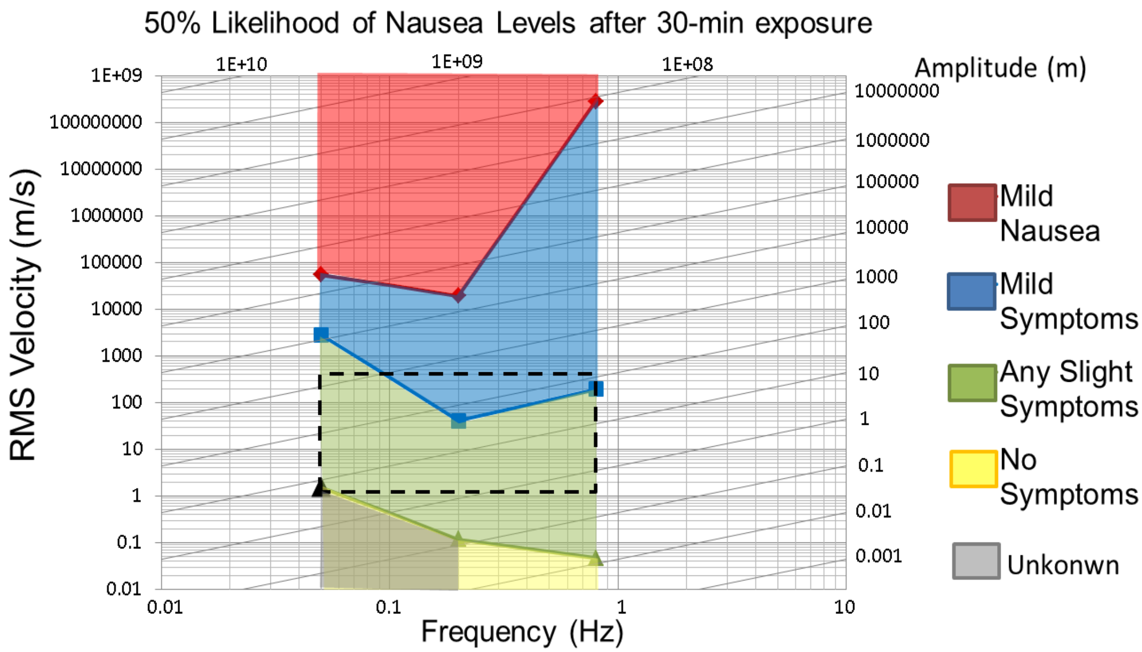


Figure 6.8 The 50% likelihood of nausea levels after 30-min exposure plotted against r.m.s. velocity v.s. frequency (with diagonal axis of amplitude). Four levels of nausea ratings (yellow: “No symptom”; green: “Any slight symptoms”; blue: “Mild symptoms”; red: “Mild nausea”) were interpolated in different areas of r.m.s. velocities and frequencies. Grey represents the unknown area due to poor fit at 0.05 Hz for “Any slight symptoms”. Dotted black box contained experimental data from the Experiment VIMS2.

Table 6.2 Details of fits of a log-linear regression line with the % of participants reaching a certain level of nausea (first column) as the 'Y' variable and the stimuli's velocities as the 'X' variables. Data are grouped according to the frequency of visual oscillations (second column). Depending on the frequency, number of data points for each regression analyses ranged from 3 to 4 (hence degrees of freedom, DOF, ranged from 2 to 3). NB: the 30% likelihood are also calculated for the latter discussion.

Regression Results of 50% and 30% Likelihood of Nausea							
	Freq (Hz)	DOF	R-square	Coefficient	Intercept (@1m/s)	Estimated velocity for 50% likelihood	Estimated velocity for 30% likelihood
Any Slight Symptoms	0.05	3	0.0667	-0.0166	0.676	not used	not used
	0.2	2	0.4286	0.0555	0.6184	0.11844	0.00322
	0.8	3	0.36	0.0333	0.6018	0.04703	0.00012
Mild Symptoms	0.05	3	0.363	0.0388	0.1919	2809.39	16.2174
	0.2	2	1	0.222	-0.3211	40.3927	16.4077
	0.8	3	0.5556	0.0555	0.2082	192.0312	5.22813
Mild Nausea	0.05	3	0.363	0.0388	0.0765	54992.30	317.446
	0.2	2	0.75	0.0555	-0.0482	19486.505	530.529
	0.8	3	0.4	0.0222	0.0679	283852122	34716.0

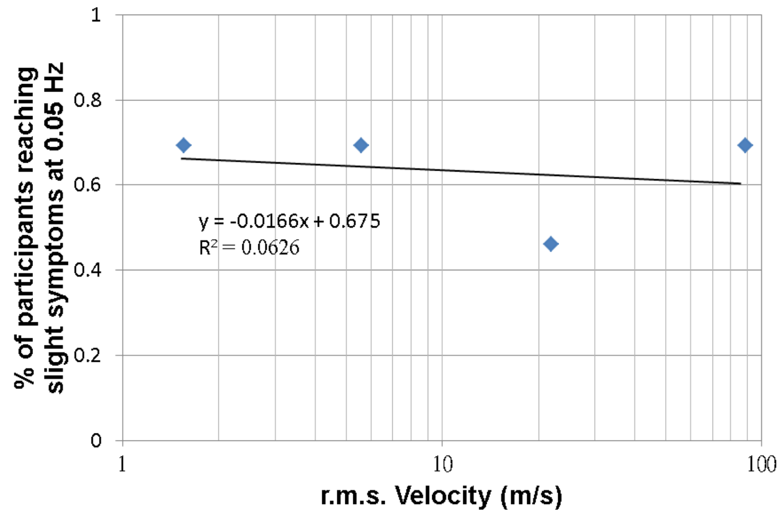


Figure 6.9 The raw regression plot for % of participants who reported 'any slight symptoms' or higher after 30 minutes of exposure to 0.05 Hz visual oscillations with 4 different velocities. NB: due to poor R-square value, this regression line was not used to predict the 50% (or 30%) likelihood data.

As shown in Figure 6.8, four 50% likelihood regions are coded in colours of yellow, green, blue, and red, representing the predicted proportion of 50% population are readily susceptible for symptoms of (i) no symptom; (ii) any slight symptoms, (iii) mild symptoms, and (iv) mild nausea, respectively. In addition, a grey area is coded as the prediction area with uncertainty.

Unlike vection, the interpretation of the nausea likelihood curves seems more complicated. For the same levels of amplitude, higher frequencies accompany with higher levels of nausea ratings when amplitude is below around 10000m. If amplitude is above 10000m, the predicted nausea levels at 0.2 Hz tend to be higher than those at 0.05 Hz and 0.8 Hz. On the other hand, for the same levels of r.m.s. velocity below around 40 m/s, similar levels of nausea are predicted for all frequencies within 0.05 Hz to 0.8 Hz. When r.m.s. velocity is above 40 m/s, higher sickness levels are expected at 0.2 Hz compared with the lower or the higher frequencies of 0.05 Hz and 0.8 Hz, respectively. It is acknowledged that the prediction results of the likelihood graph for nausea are somehow different from the conclusions about the two-frequency-responses of nausea made in Chapter 5, especially for large values of amplitude or velocity. The findings in Chapter 5 suggest flat lines across different frequencies. After all, while the conclusions in Chapter 5 were based on statistical significance, the likelihood graphs in this Chapter are based on the % of participants reporting certain levels of VIMS. Also, all predicted non-linear changes were predicted values outside the ranges of experimental conditions in Experiment VIMS2. In other words, they were beyond the conditions that were studied. Hence, no contradiction with results presented in Chapter 5. When velocity and amplitude approach large values beyond the range of this study, the trends showed in Figure 6.8 about nausea severity are, instead, consistent with the trend of the frequency responses for average nausea ratings at 30 min when keeping r.m.s. velocity or amplitude at high values (i.e., 89 m/s and 100 m, respectively; Figure 6.10). A trend of higher nausea levels occurred at 0.2 Hz than lower or higher frequencies can be observed from Figure 6.10 although not statistically significant.

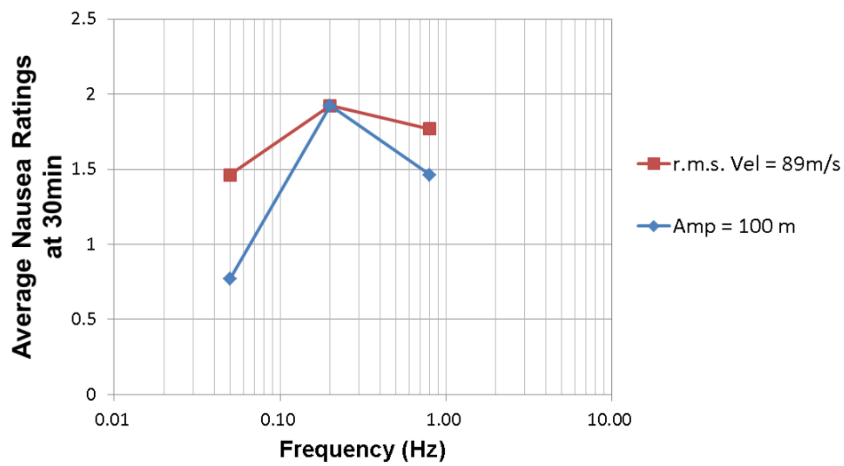


Figure 6.10 Average nausea ratings at 30 min collected from Experiment VIMS2 were plotted against frequency with three levels of constant r.m.s. velocities (5.6 m/s, 22 m/s, and 89 m/s).

As shown in Figure 6.8, data investigated in Experiment VIMS2 only covered the 50% likelihood regions of slight to mild symptoms. This suggests that the conditions studied in Experiment VIMS2 had not been strong. Since only 33% of the Hong Kong Chinese are susceptible to VIMS (So *et al.*, 1999), it is, perhaps, not surprising that a 50% likelihood did not cover the region for higher levels of nausea. Using data in Table 6.2, the 30% likelihood graph is drawn in Figure 6.11. The choice of 30% is made to be consistent with the 33% prevalence of VIMS susceptibility.

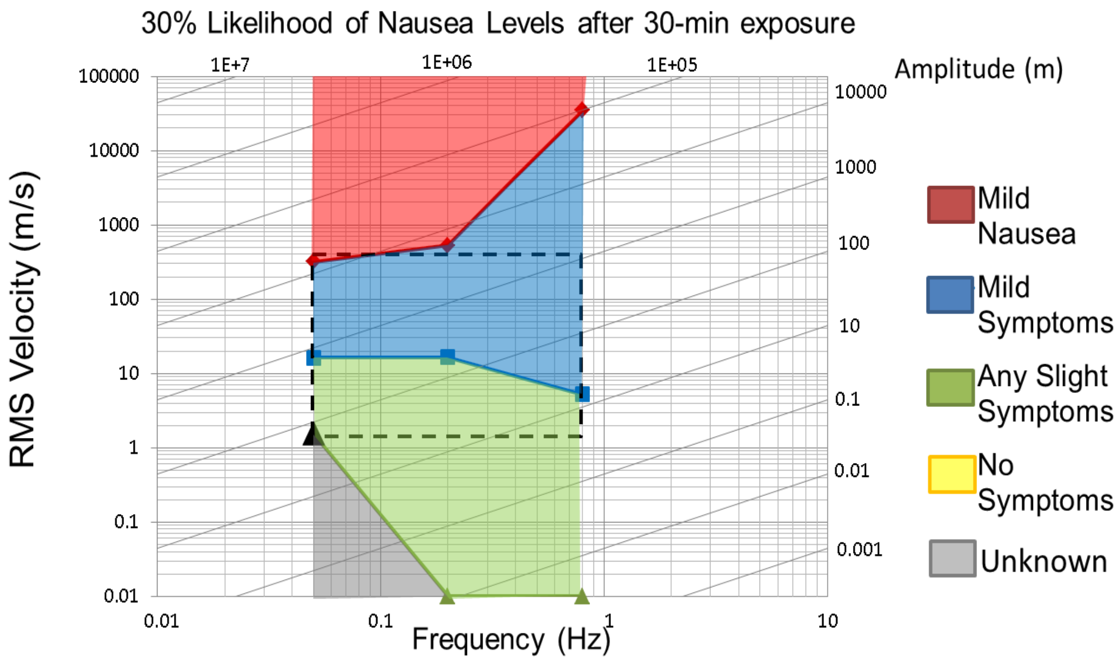


Figure 6.11 The 30% likelihood of nausea levels after 30-min exposure plotted against r.m.s. velocity v.s. frequency (with diagonal axis of amplitude). Four levels of nausea ratings (yellow: “No symptom”; green: “Any slight symptoms”; blue: “Mild symptoms”; red: “Mild nausea”) were interpolated in different areas of r.m.s. velocities and frequencies. Dotted black box contained experimental data from the Experiment VIMS2. Similar to Figure 6.8, grey coloured area represents the unknown area due to poor fit at 0.05 Hz for “Any slight symptoms”. Predicted data which are below 0.01 m/s are rounded up to 0.01 m/s.

6.4 Discussion

The likelihood curves are proposed in this chapter to unify the two frequency responses of vection or VIMS and predict the incidence of them in terms of visual stimuli parameters (i.e., velocity, frequency, and amplitude). Despite the promising applications of the current method, interpretation of the results require special caution in the following aspects.

On one hand, the prediction accuracy of the current likelihood graphs can be improved with data availability, especially for VIMS. Note that the goodness of fit (R-square) of the VIMS likelihood curves (see Table 6.2) are relatively low while those of the vection likelihood curves (see Table 6.1) are basically higher than 90%. One reason is that the number of available data points (or DOF) for the regression analyses of VIMS were limited compared to those of vection. Although collecting VIMS data are more time consuming, in the future it is worth doing it to improve the fits of the current percentage likelihood graph for VIMS for the benefit of itself.

On the other hand, caution should also pay to the scope of use of the current likelihood curves. All stimuli that used in this study are oscillations moving along the fore-and-aft axis of the viewers. However, Lo and So (2001) found that visual motion with different axes evoked different levels of VIMS. Therefore, different versions of the likelihood curves of vection and VIMS may be developed for different axes of visual motion in the future for the convenience of use. As discussed in Section 7.2, although evidence has shown that the general shape of frequency response of VIMS will remain when axis of motion changed from fore-and-aft to roll, lateral, and yaw axes, the peaks will shift according to the axis of motion. Also, effects of scene complexity and FOV have not been accounted for in these 50% likelihood graphs. Future work to improve the visualization is desirable.

After all, applying the likelihood graphs for presenting the two-frequency-response results of both VIMS and vection is advantageous. Firstly, it clears the ambiguity of the term “frequency response” and enables comparisons between different studies. Secondly, it could be an ideal tool for game / virtual reality designers as it is possible to exactly manipulate visual stimuli in order to achieve certain level of VIMS and vection, respectively.

6.5 Conclusion

As discussed above, although the absolute values of velocities may vary with changes of scene complexity and axis of motion, the general shape of the frequency response has been to be consistent between Experiments VIMS1 and VIMS2 in this study and across different stimuli in roll axis (Lin *et al.,* 2005), lateral, yaw, and fore-and-aft axes (Chen, 2006) (see Section 7.2). Consequently, instant applications of the current figures could be used as guidance for relative adjustments by display/movie/video game designers to enhance or control the perception of vection and the possible incidence of VIMS. The results of this study indicate that certain levels of vection as well as VIMS can be manipulated by manipulating the basic parameters of visual motion such as velocity, frequency, or amplitude. Accuracy of the current likelihood graphs would be enhanced with more data from studies in the future.

CHAPTER 7: DISCUSSION: HOW THE CURRENT FINDINGS FIT INTO EXISTING LITERATURE

SUMMARY

Two major findings related to VIMS have been described previously in Chapter 5: (i) frequency responses of VIMS are flat when velocity is fixed; (ii) frequency responses of VIMS show increasing trends when amplitude is fixed. This chapter discusses how these two findings match into the existing literature. In particular, Section 7.1 will address the contradiction and agreement between the current finding of a flat frequency response of VIMS with the findings in Duh *et al.* (2004); Diels and Howarth (2012) and So *et al.* (2001a). In Section 7.2, the findings that VIMS will increase with increasing frequency of visual oscillations are compared and extended with the existing literature to form a body of literature concerning the frequency responses of VIMS with visual stimuli across different axes and presented in different field-of-view. Data collected in the current study was analyzed to support the 'Spatial Velocity (SV)' hypothesis proposed in So *et al.* (2001a) (Section 7.3) and Cybersickness Dose Value (CSDV) models are constructed and used to predict selected data in Experiment VIMS2 (Section 7.4).

7.1 Major Finding 1: Frequency responses of VIMS with constant r.m.s. velocity

As mentioned in Chapter 2, two clusters of previous studies have investigated the frequency responses of VIMS for observers viewing visual oscillations and reported that the levels of VIMS would be the highest when the stimuli's frequency is about 0.06 Hz and 0.2 Hz, respectively. The key study behinds the 0.06 Hz prediction is Duh *et al*. (2004) and the key study behinds the 0.2 Hz prediction is Diels and Howarth (2012). Both studies kept the stimuli's velocities constant. Contrary to both studies, this thesis found that VIMS was independent of frequency when the stimuli's velocities were kept constant (see Chapter 5). The differences and relations of the current study and the two previous studies are explained in the following paragraphs starting with a critical review of Duh *et al*. (2004) and Diels and Howarth (2012).

7.1.1 A critical review of Duh *et al*. (2004)

It is not the intention of the author to criticize Duh *et al.* (2004). In fact, the author is thankful for this study to trigger the motivation of the author to study the frequency responses of VIMS. Nonetheless, because the current findings contradict with the past study, it is the duty of the author to explore all possible reasons in details. In Duh *et al*. (2004), the assertion about VIMS peaking at around frequency of 0.06 Hz was derived in three steps. Firstly, Duh *et al*. constructed a frequency response curve of the visual self-motion system by combining self-motion perception data from Berthoz *et al*. (1979) and their own data collected from two experiments, in which participants were exposed to visual scene roll oscillation either presented on a head-mounted display (HMD) or projected on a custom-made plastic dome. Secondly, the derived visual response curve was normalised and plotted together with a vestibular response curve cited from Jones and Milsum (1965), as shown in Figure 7.1. These two response curves intersected at the frequency about 0.06 Hz (the cross-over frequency), at which Duh *et al*. hypothesized that the levels of VIMS should be most readily evoked since the summed gain from the visual and vestibular self-motion systems is maximum. Lastly, this hypothesis was further examined by a third experiment, in which participants were exposed to concurrent and conflicting visual (yaw oscillating images presented in HMD) and vestibular (a rotational chair) motion at around 0.06 Hz and 0.2 Hz. Results of their third experiment confirmed conflicting cues with frequency content at 0.06 Hz provoked significantly higher levels of VIMS than cues at 0.2 Hz.

It should be noted that there were several problems in their findings. To begin with, motion sickness and postural instability were not measured within the same experiment and not under the same types of oscillations. Also, the determination of the cross-over frequency at 0.06 Hz is subjected to possible variations. The intersection of the visual-vestibular response curves as shown in Figure 7.1 is subject to a rightward shift if the frequency range investigated begins from 0.1 Hz or a leftward shift if from 0.01 Hz, resulting in a higher or a lower value of the "specific" cross-over frequency (see Figure 7.2). Last but not least, only two frequencies (0.05 Hz and 0.2 Hz) were used to verify the cross-over frequency hypothesis. Although stronger motion sickness was found at 0.05 Hz condition then at 0.2 Hz, it might be pre-mature to claim the frequency responses of VIMS will peak at 0.06 Hz.

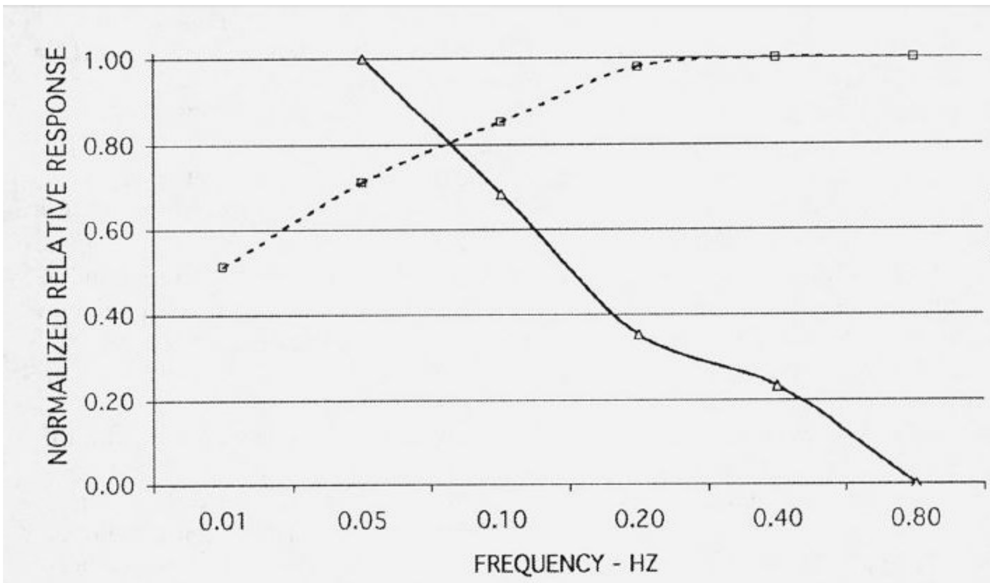


Figure 7.1 Cross-over of visual frequency response (solid curve) and vestibular frequency response (dotted curve) (copied from Duh *et al*., 2004).

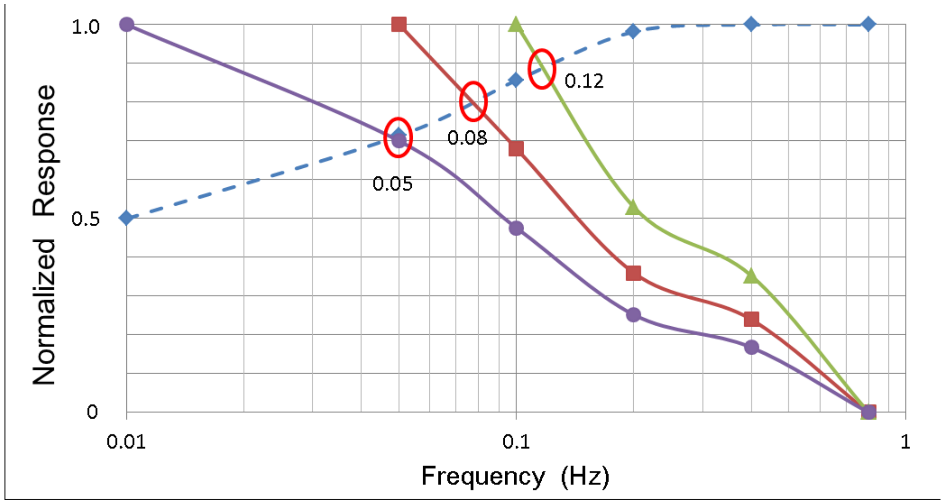


Figure 7.2 A simulation of the leftward and rightward shifts of the cross-over frequency. Vestibular response (dotted curve) intersects with three different visual responses (solid curves) derived from different frequency ranges. This suggests that 0.06 Hz may not be the only possible intersecting frequency.

7.1.2 A critical review of Diels and Howarth (2012)

Similar to Section 7.1.2, it is not the intention of the authors to criticize any past study. Again, the author is grateful to Diels and Howarth for triggering the motivation of the current study. Since there is a difference between their findings and our findings, all possible explanation should be explored. In Diels and Howarth (2012), frequency-dependence of VIMS were studied in two experiments with participants exposed to random dot optical flow patterns oscillating along the fore-and-aft axis. In the first experiment with the investigated frequency range from 0.025 Hz to 0.2 Hz, Diels and Howarth found VIMS increased with increasing frequency, while in the second experiment with a higher frequency range from 0.2 Hz to 1.6 Hz, they found that VIMS reduced with increasing frequency. Joining results from these two experiments, as in Figure 7.3, Diels and Howarth asserted that VIMS peaked at frequency of 0.2 Hz. However, it might be possible that the effects of frequency might have been confounded with the effects of individual characteristics since different groups of individuals participated in the two experiments. Also, it was unfortunately that 0.2 Hz was at the end of the range for both experiments.

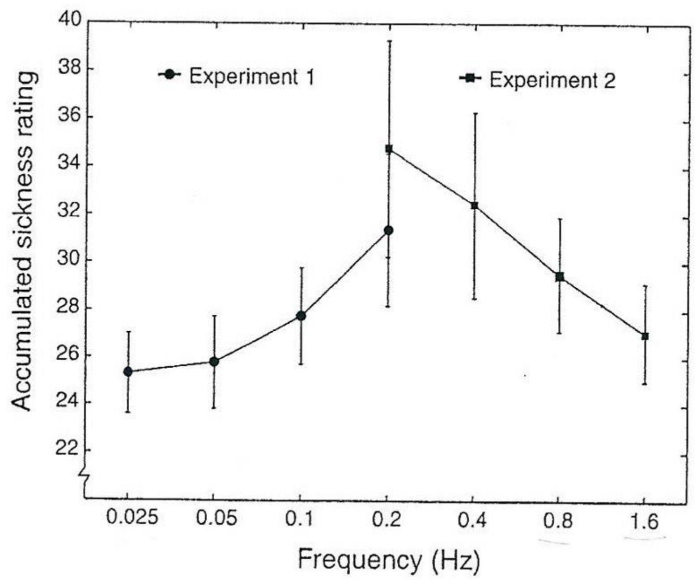


Figure 7.3 The frequency response of VIMS peaked at 0.2 Hz by combining results from two experiments in Diels and Howarth (2012) (quoted from Diels and Howarth (2012).

7.1.3 A critical review of the current findings at 0.06 Hz and 0.2 Hz

Different from the two previous studies, VIMS was found to be similar regardless of the change of frequency in the current experiments, whose results have been described elaborately before in Chapter 5. In the first experiment (Experiment VIMS1), postural instability data were collected together with VIMS and a frequency range that covered 0, 0.05, 0.1, 0.2 and 0.8 Hz was investigated. Similar to the Duh *et al.* (2004) and Diels and Howarth (2012), r.m.s. velocity was kept constant. Although no significant effect of frequency was found in changing the levels of VIMS, the results were found to be partially aligned with the previous findings with observed larger inter-subject variability at measured nausea when exposing to 0.2 Hz oscillations and larger inter-subject variability at measured postural sway when exposed to 0.05 Hz oscillations. Of course, one could argue that the non-significant changes in levels of VIMS might be due to the use of weak and non-provoking stimuli. However, the fact that significantly higher levels of nausea was reported after exposure to oscillations at 0.05, 0.1, 0.2 and 0.8 Hz than watching the stationary condition (0 Hz oscillation) could rule out the hypothesis of a weak stimuli. Furthermore, the current finding in Experiment VIMS1 was repeated in Experiment VIMS2 when the same stimuli as in Diels and Howarth (2012) were used. In summary, both Experiment VIMS1 and VIMS2 have congruently showed that when watching visual oscillations with a single level of velocity, changing frequency of that oscillations would not affect the levels of VIMS that it will provoke.

It is worth noting that the current finding is consistent or supportive to a hypothesis proposed by So *et al*. (2001a). As introduced in the literature review (Chapter 2), So *et al*. (2001a) proposed a metric, refers to spatial velocity (SV), to quantify visual movement. Increasing SV was found to significantly increase VIMS. This finding not only showed that VIMS was dependent on SV but also implied that for visual oscillations with similar scene complexity and similar velocity, the same level of VIMS will be provoked. This agrees with the current finding.

7.2 Major Finding 2: Frequency responses of VIMS with constant amplitude

The current results indicated that, when watching visual oscillations with constant amplitudes, levels of VIMS increased with increasing frequency and the ranges of frequencies that are associated with higher VIMS varied from 0.2 Hz to 3.2 Hz depending on the values of the constant amplitudes. This finding is consistent with the findings in Lin *et al.* (2005) and Chen (2006) who reported that levels of VIMS after watching visual oscillations will increase as the frequency of oscillations increased from 0.035 Hz (or 0.0375 Hz) to 0.08 Hz, 0.2 Hz, or 0.38 Hz depending on the individual experiments. This consistency is quite remarkable considering the many differences among the three studies in scene complexity, axis of visual movements, FOV, etc. The findings that the frequency of oscillations that are most provocative will depend on the levels of constant amplitudes suggest that the levels of oscillation velocity is an important influence of VIMS because the r.m.s. velocity of an oscillation is proportional to the product between the oscillating frequency and the amplitude of oscillation. This is consistent with the SV hypothesis proposed in So *et al.* (2001a).

In the current study, levels of VIMS reached their significant highest points when the oscillation frequency was also at the highest end of the ranges (0.0125 Hz to 0.8 Hz for amplitude = 100 m; 0.05 Hz to 3.2 Hz for amplitude = 6.25m). Intuitively speaking, as the frequency keeps increasing, levels of VIMS should reduce. Slight evidence is found when the oscillation amplitude was kept at 100m, levels of VIMS peaked at 0.2Hz and reduced at 0.8Hz but the reduction was not significant. In both Lin *et al*. (2005) and Chen (2006), levels of VIMS reduced after reaching their peaks although only Chen (2006) reported the statistics supporting the reduction (Figures 7.4 and 7.5). Combining the three studies, it is reasonable to believe that levels of VIMS will increase, peak and reduce with increasing oscillation frequency although the absolute values will depend on the level at which the constant oscillating amplitude is held.

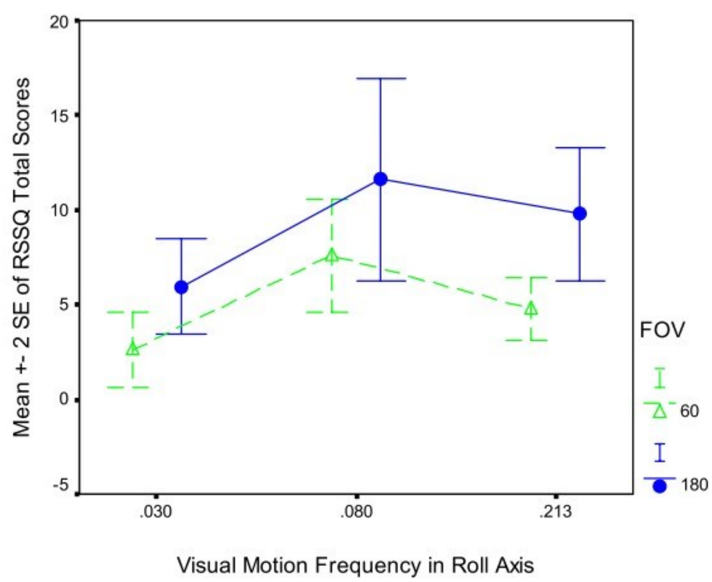


Figure 7.4 The frequency responses of VIMS (represented by revised-SSQ total scores) for two FOVs of stimuli (60° and 180°) (adopted from Lin *et al.*, 2005)

A review of Lin *et al.* (2005) and Chen (2006) as well as Experiment VIMS2 of the current study indicated that while the findings are consistent among the three studies, they have different short-comings and strength that can complement each other. First, both Lin *et al.* (2005) and Chen (2006) have only used one level of constant amplitude but Experiment VIMS2 studied multiple levels of oscillating amplitude and reported that the trend of increasing VIMS with increasing frequency held for different amplitude although, as expected, the absolute value of the frequency at which VIMS was the highest are different. Secondly, Lin *et al.* (2005) repeated the study with two levels of field-of-view (FOV) (60 degrees horizontal and 180 degrees horizontal, see Figure 7.4) and reported that levels of VIMS the shape of frequency responses hold for both FOVs. Last but not least, Chen (2006) repeated her study with three axes of visual motion: fore-and-aft, lateral and yaw axis and reported that the general shape of frequency responses hold for all three axes of visual motions (see Figure 7.5).

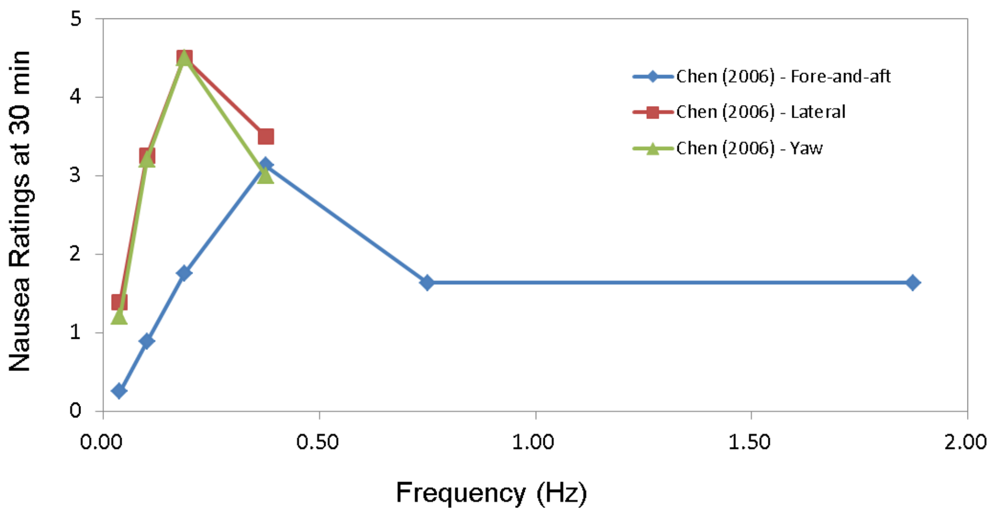


Figure 7.5 Frequency responses of nausea ratings after 30-min exposures to visual oscillations along fore-and-aft, lateral, and yaw axes, adapted from Chen (2006).

In summary, the findings that levels of VIMS increase, peak and reduce with increasing frequency of visual oscillations with constant amplitude agree remarkably among the current study, Lin *et al.* (2005) and Chen (2006) although the absolute details of the frequency at which VIMS peaks are different. Results of the current study suggest that the differences in the frequency at which VIMS will peak can be explained by the differences in the constant stimuli's amplitudes. The fact that Lin *et al.* (2005) found similar shape in the frequency responses of VIMS (increase, peak and reduce) with two levels of FOVs and Chen (2006) found similar shape in the frequency response of VIMS with visual oscillation in fore-and-aft, lateral and yaw axes suggest that this shape of frequency response is robust across many conditions. With the addition of data from the current study, one can predict that the frequency at which VIMS will peak will increase with increasing stimuli's amplitude and the findings are likely to be generalized to studies with visual oscillation in both rotational and translational axes as well as different FOVs.

7.3 Consistency with the Spatial Velocity (SV) hypothesis

So *et al.* (2001a) proposed to use a measuring metric called 'spatial velocity (SV)' to measure and quantify the strength of a VIMS provoking visual stimuli. It has been reported that this SV is linearly related to levels of nausea among viewers exposed to the visual stimuli. However, the linearly relationship was only tested using data collected in two pilot experiments manipulating three levels of scene complexity of the stimuli (with velocity and amplitude of stimuli held constant) and three levels of stimuli velocity (with scene complexity and amplitude held constant). Conditions with different combinations of stimuli amplitude and frequency were not tested. In the current study, levels of VIMS has been examined under 17 combinations of stimuli's amplitude and velocity and they could be used to test the SV hypothesis which predicts that as SV increases, levels of VIMS increase linearly.

The SV is the product between 'a measure of contrast complexity of the visual stimuli' and the 'velocity' of the stimuli. SV is directional specific. In So *et al.* (2001a), the contrast complexity of a visual stimulus is measured by the average spatial frequency (SF) (cycles per degree) in three axes (horizontal, vertical and radial) of a series of representative sampled screen shots of the visual stimuli. Details of the measurement are documented in So *et al.* (2001a). Yuen (2002) reported a matlab™ program to measure the SF of a captured movie of a visual stimulus. For Experiment VIMS2, the visual stimulus was a star-field (see Chapter 3) and the SF in radial axis is 0.32 cycles per degree (cpd). To calculate the associated SV along fore-and-aft axis, the radial SF was simply multiplied by the r.m.s. velocity of that condition. In Experiment VIMS2, the scene complexity was kept the same.

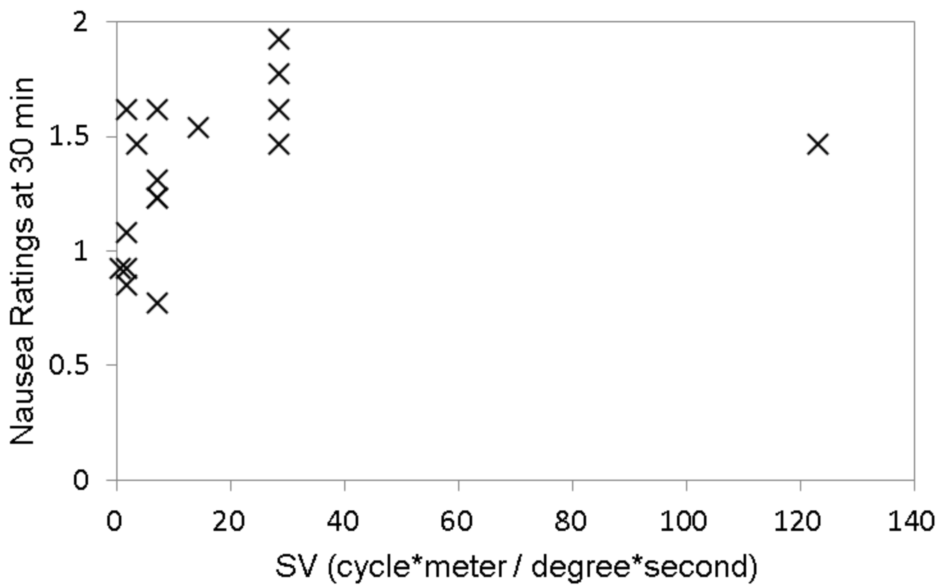


Figure 7.6 Levels of average nausea from 13 participants in Experiment VIMS2 plotted as functions of SV of the visual stimuli. Nausea is collected after 30 minute exposure to a star-field pattern zooming in and out along the fore-and-aft axis. SV along the fore-and-aft direction are calculated for 17 conditions with different combinations of stimuli's amplitudes and velocities.

Inspections of Figure 7.6 indicated a non-linear effect. As SV increased, levels of nausea increased and then became steady. This suggests that the linearly relationship reported in So *et al.* (2001a) is not corrected. Since the range of the SV in Figure 7.6 was much larger than that in So *et al.* (2001a). This finding is new, original and useful as determining the true relationship between nausea and SV will be critical to the use of SV to predict levels of nausea. In fact, So *et al*. (2001a) predicted a possible non-linear relationship as the range of SV increases and proposed an equalization weighting method to linearize the relationship (see next section).

7.4 Predicting levels of nausea using the previously reported CSDV methodology

Building on the SV metric, So *et al*. (2001a) further developed a dose value for predicting the severity of cybersickness (a type of VIMS). The dose value was referred to as the cybersickness dose value (CSDV), analogous to the motion sickness dose value (MSDV) proposed by Griffin (1990) for prediction of seasickness. The CSDV model is an objective and quantitative measure taking three main parameters into account, i.e., scene velocity (V), scene complexity (SF), and exposure duration (T), in the following form:

$$\mathrm{CSDV} = \int_0^T \mathrm{SV}\,\mathrm{d}t = \int_0^T (\mathrm{V} * \mathrm{SF})\,\mathrm{d}t$$

Note: SV is a product of scene velocity and scene complexity. Scene complexity is quantified using average of radial spatial frequencies for the sampled snapshots of a stimulus. The detailed method of SF calculation was documented in So *et al*. (2001a). The CSDV of a particular stimulus with an average SF with known exposure duration (T) can be estimated as a product of the r.m.s. velocity ($V_{r.m.s.}$), SF, and T (i.e., CSDV = $V_{r.m.s.}$ * SF * T).

Inspections of Figure 7.6 indicated that the levels of nausea changed in a non-linear way with increasing SV. As explained in Chapter 5, data collected with visual oscillations with constant velocity but different amplitude (hence, frequency) provoked similar levels of nausea (see Figure 5.13a). These data did not contribute much to the non-linear relationship between nausea and SV as shown in Figure 7.6. On the contrary, data collected with visual oscillations with constant amplitude but different velocity (hence, frequency) provoked higher sickness as the velocity (or frequency) increased (see Figure 5.13b). These effects were the cause of the non-linear effects as shown in Figure 7.6. Out of the 17 conditions in Experiment VIMS2, 13 conditions had constant amplitude (at three levels) with different velocities. Data from these 13 conditions were plotted in Figure 7.7(a). The remaining 4 conditions that were left out served a convenience purpose – to be left out from the CSDV model construction so that they can be used as target data set to verify the predictive ability of the CSDV model.

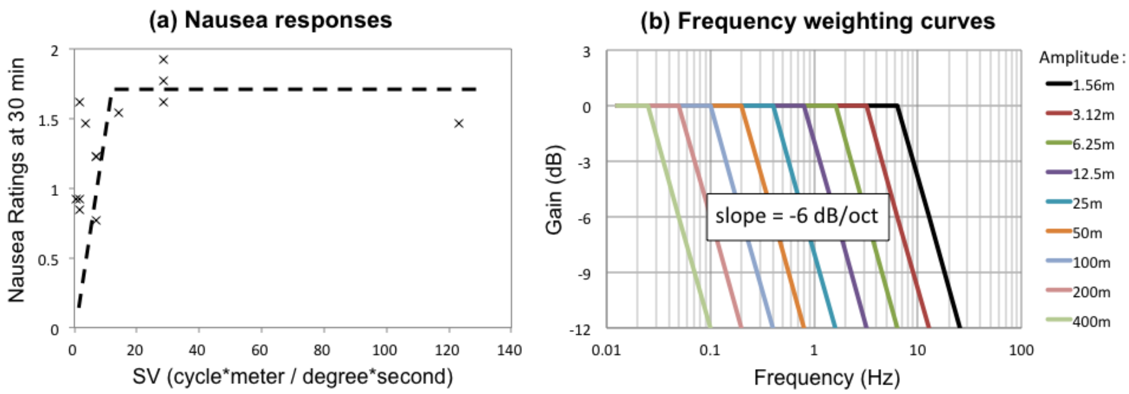


Figure 7.7 (a) Average nausea levels as a function of SV. Only data collected in Experiment VIMS2 with constant amplitudes and different velocities are included in the figure. There are 13 data conditions (2 of them completely overlapped). The non-linear effects can be approximated by two piece-wise linear lines: one from the origin to around the data point with velocity of 44.4 m/s (SV = 14.2 cycle*meters per degree*second) jointed by another horizontal line extending all the way to right. (b) A series of equivalent frequency weighting curves for the piece-wise approximation of velocity weighting. The frequency weighting curves are a series of low-pass analog filters with cutoff frequencies as functions of the stimuli's amplitude (see Table 7.1). For each filter, the gain is 0 dB if frequency is below its cutoff frequency, above which the gain declines at a slope of -6 dB per octave. These frequency weighting filters are for illustration only as the velocity weighting was implemented using direct scaling in the current study.

A piece-wise linear relationship between nausea ratings and SV was observed and approximated by a broken dotted line in Figure 7.7(a) with its cutoff point at SV at 14.2 cycle*meters per degree*second (cmpds) (or velocity = 44.4 m/s). Since stimuli's spatial frequencies were kept constant (SF = 0.32 cpd) in the current study, the SV weighting curve was indeed a velocity weighting curve. This indicated possible applications of a velocity-weighted SV when calculating the CSDV of a stimulus. However, in the context of signal processing, the SV signals '*SV(t)*' should normally be processed in the time domain using a filter with pre-determined frequency response. Note that frequency weightings (i.e., filters) have been employed to predict motion sickness caused by vertical oscillation on ships in previous studies (BS 6841; ISO 2631; Lawther and Griffin, 1987). In those studies, frequency weightings had been implemented using analog filters.

Following the tradition of BS6841, the velocity weighting function in Figure 7.7(a) has been mathematically mapped into a series of frequency weighting functions (i.e., filters) in Figure 7.7(b). These frequency weightings were characterized as low-pass filters with various cutoff frequencies that depended on the stimuli's amplitudes (i.e., the larger a stimulus' amplitude was, the smaller of a cutoff frequency the filter should have). A slope of -6 dB/oct above the cutoff frequencies was adopted in all the frequency weighting functions, corresponding to the plateau section of the velocity weighting function in Figure 7.7(a). The logic is that the filter will reduce the influence of SV when it is beyond 14.2 cmpds so that any increases beyond 14.2 cmpds will be neutralized. Nine examples of the frequency weighting functions were displayed in Figure 7.7(b) corresponding to the range of stimuli's amplitudes that had been used in the current study. The one-to-many relationship between velocity weighting function and frequency weighting function is summarized in Table 7.1.

Table 7.1 A summary of the cutoff points for the velocity weighting function and the example frequency weighting functions as shown in Figure 7.7(b)

Velocity weightings	**Corresponding Frequency weightings**	
cutoff velocity (m/s)	amplitude (m)	cutoff frequency (Hz)
	...	...
	1.56	0.025
	3.12	0.05
	6.25	0.1
	12.5	0.2
44.4	25	0.4
	50	0.8
	100	1.6
	200	3.2
	400	6.4
	...	...

To verify the CSDV model, Figure 7.7(a) has been redrawn as Figure 7.8(a) with the x-axis transformed into CSDV (product of SV and T (T=30x60seconds)). To linearize the non-linear effect, the frequency weighting curves as shown in Figure 7.7(b) were applied. Theoretically, the processing procedure of the CSDV signals should be as follows: the time series of the SV function of a stimulus during the exposure has to pass through the appropriate low-pass filter, and then the filtered SV function is integrated in time to calculate a CSDV for the stimulus. However, in this study, this procedure has been simplified by assigning appropriate scaling factors (could be non-linear mapping) to the r.m.s. SV of a stimulus according to the velocity weightings as shown in Figure 7.8(a). For example, for data collected from conditions using stimuli with amplitude equals to 25 m, data points will remain unchanged if their associated SV are below 14.2 cmpds, otherwise their SV values will be collapsed to 14.2 cmpds even though the real SV were greater than 14.2 cmpds.

Besides the velocity weighted models, a more general model – the logarithm-transformed model – was proposed in additional to the weighted model. In Figure 7.8(c), the data points in Figure 7.8(a) are plotted using natural logarithm of CSDV (Log-CSDV). For each figure, a linear regression line was fitted and the R-square values are 0.114, 0.454, and 0.378 respectively for Figure 7.8 (a), (b), and (c).

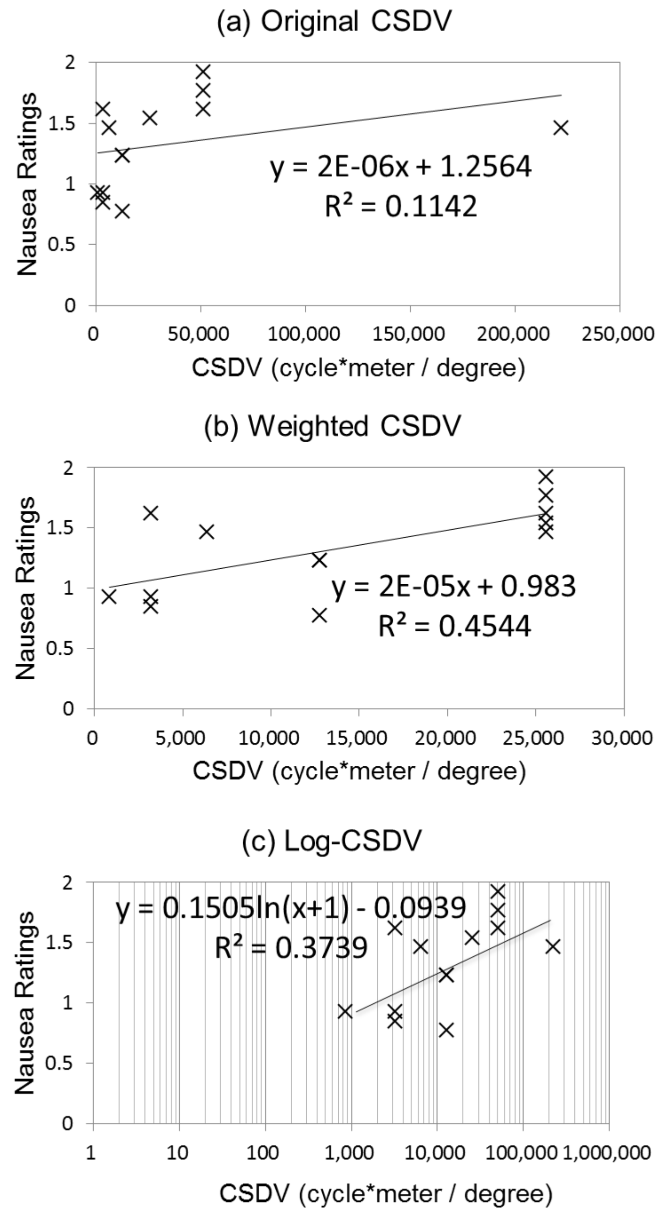


Figure 7.8 Fitting data from the current study into the CSDV model. (a) Original CSDV; (b) after velocity-weighted; (c) reploted using log CSDV. Each graph has 13 data points (2 data points were completely overlapped).

The weighted CSDV model and the log-CSDV model both demonstrate a better fit than the original CSDV model. Therefore they will be used to predict the average nausea ratings for the four conditions that have not been involved in the derivation of the current frequency weightings as well as the five conditions in another experiment – Experiment VIMS1.

From Figure 7.8(b), the fitted linear equation for the weighted CSDV model is extracted and listed below as:

$$\text{Average Nausea Ratings} = 0.00002 * \text{Weighted CSDV} + 0.983$$

Note that the non-zero intercept in the equation means that for viewers exposed to stationary visual stimuli (i.e., CSDV=0) for 30 minutes, they could experience some slight extent of sickness. This can be justified by the fact that the nausea ratings at 30 min reported at the 0 Hz (without motion) condition in Experiment VIMS1, in which twelve participants reported nausea ratings ranging from 0 to 2 with an average of 0.4.

As mentioned above, there are four conditions (see Table 7.1) that have not been engaged in the development of the weighted CSDV model. The data in these conditions are used to verify the validity of the new model. The conditions' parameters and their prediction details are listed in Table 7.1 and shown in Figure 7.9. Except for condition 13, the prediction errors are less than or equal to 5%. Although there is a 23% error for predicting the average nausea value for condition 13, it is acceptable considering that the four conditions cover wide ranges of frequency, velocity, and amplitudes. Therefore, the weighted CSDV model is validated.

Table 7.2 Prediction results of the velocity-weighted CSDV model as shown in Figure 7.8(b)

Condition	Freq (Hz)	r.m.s.Vel (m/s)	Amp (m)	Weighted CSDV	Predicted Nausea	Measured Nausea	Error
3	0.4	22	12.5	12787.2	1.239	1.308	5%
13	0.1	22	50	12787.2	1.239	1.615	23%
14	0.05	89	400	25574.4	1.494	1.462	2%
17	0.8	5.6	1.56	3225.6	1.048	1.077	3%

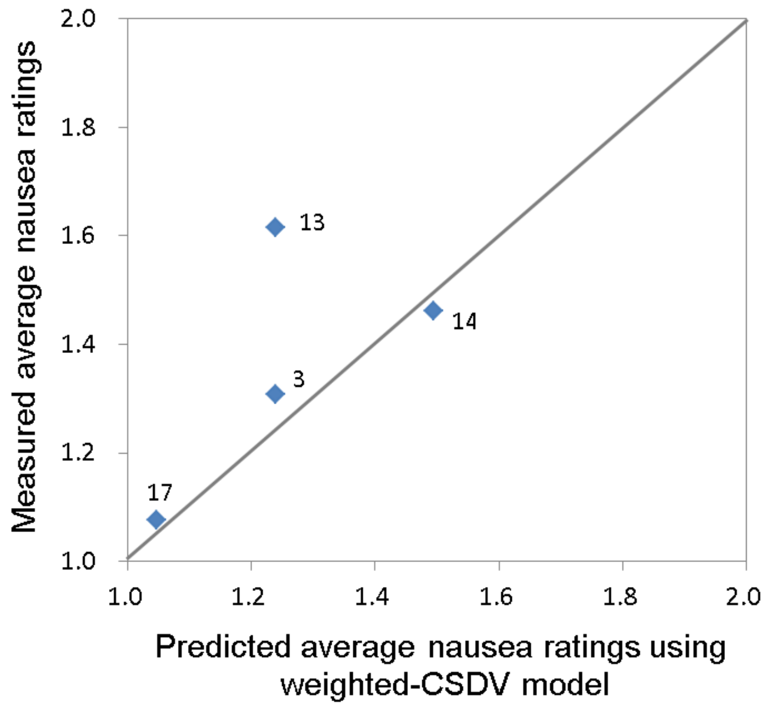


Figure 7.9 Measured average nausea ratings v.s. predicted average nausea ratings for conditions 3, 13, 14, and 17 in Experiment VIMS2 using the weighted CSDV model as shown in Figure 7.8(b). The numbers beside each data point are the condition numbers.

As shown in Figure 7.8(c), the fitted equation of the log-CSDV model was presented below:

$$\text{Average Nausea Ratings} = 0.1512 * \ln(\text{CSDV} + 1) - 0.0966$$

Note that the optimal linear regression of the logarithmic model suggested a negative value of intercept (i.e., -0.0966). This is obviously not reasonable since there is no definition about the negative values of nausea ratings. Hence, the logarithmic model was modified with forcing the intercept to be 0.4 (which was the average nausea ratings of the control condition in Experiment VIMS1). The intercept-adjusted logarithmic model was presented in Figure 7.10, with an R-square value of 0.33.

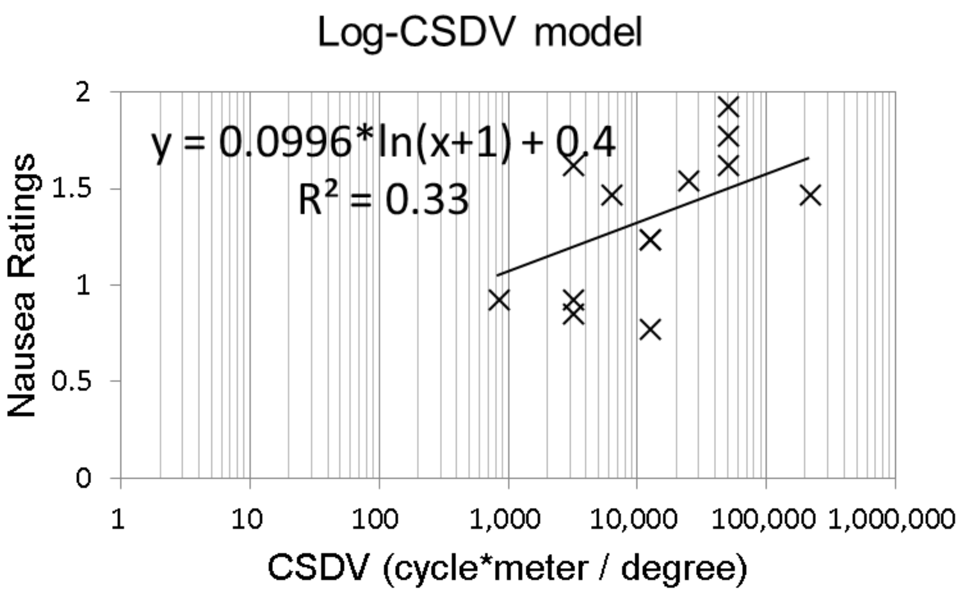


Figure 7.10 The Log-CSDV model with intercept forced to 0.4

Therefore, the fitted equation of the log-CSDV model was updated as follows:

$$\text{Average Nausea Ratings} = 0.0996 * \ln(\text{CSDV} + 1) + 0.4$$

The prediction results of the updated log-CSDV model are shown in Table 7.2 and illustrated in Figure 7.11. A comparison of the prediction results indicates that the log-CSDV model gave comparable prediction with the velocity-weighted CSDV model. In addition, the concept of the log-CSDV model is consistent with the Fechner law, which states that human's psychological sensation is proportional to the logarithm of the physical intensity of a stimulus (e.g., Stocker and Simoncelli, 2006; Takahashi, 2006). The logarithmic nature between the severity of VIMS and the CSDV of visual stimuli suggests that the log-CSDV model may be a better and psychophysically-sound alternative to the velocity-weighted CSDV model. This is new, original and important finding as So et al. (2001a) did not foresee that.

Table 7.3 Prediction results of the log-CSDV model as shown in Figure 7.10

Condition	Freq (Hz)	r.m.s.Vel (m/s)	Amp (m)	Ln(CSDV+1)	Predicted Nausea	Measured Nausea	Error
3	0.4	22	12.5	9.447	1.341	1.308	3%
13	0.1	22	50	9.447	1.341	1.615	17%
14	0.05	89	400	10.833	1.479	1.462	1%
17	0.8	5.6	1.56	8.061	1.203	1.077	12%

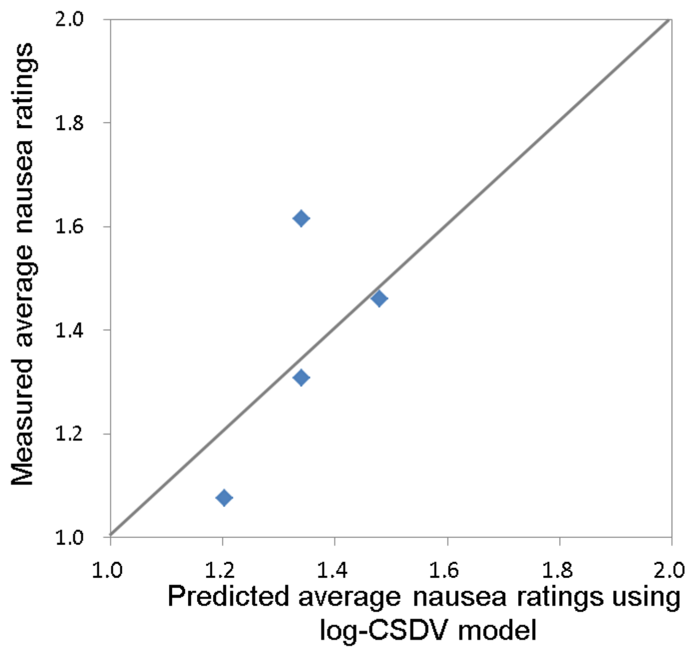


Figure 7.11 Measured average nausea ratings v.s. predicted average nausea ratings for conditions 3, 13, 14, and 17 in Experiment VIMS2 using the log-CSDV model as shown in Figure 7.10. The numbers beside each data point are the condition numbers.

In addition to predicting data collected in the same experiment (Experiment VIMS2), the weighted model and the log model have also been used to predict the results of another experiment (Experiment VIMS1). The prediction results are summarized in Table 7.3. Inspections of Table 7.3 indicate that neither model provides satisfactory predictions. The measured levels of nausea ratings are larger than the predicted values at a relatively constant level, which is around 40%. It might be explained by the fact that Experiment VIMS1 has used stimuli with a larger FOV than the stimuli in Experiment VIMS2, based on whose data the models are derived. The positive correlation between the FOV of a stimulus and the provoked levels of VIMS has been reported in previous studies (e.g., DiZio and Lackner, 1997; Lin *et al*., 2002). This indicates that the effects of FOV should be considered in the CSDV model. Future work is desired. Having said that, nausea data collected at 0.05, 0.1, 0.2 and 0.8 Hz were not significantly different from each other. This is consistent with the predicted results using both the velocity-weighted model and the log-CSDV model.

Table 7.4 Prediction results of the weighted model and the log-CSDV model for Experiment VIMS1.

Experiment VIMS1					Weighted Model			Log Model		
Condition	Freq (Hz)	r.m.s.Vel (m/s)	Amp (m)	Measured Nausea	Weighted CSDV	Predicted Nausea	error	ln(CSDV+1)	Predicted Nausea	error
1	0	0	0	0.417	0.0	0.983	136%	0.0	0.4	4%
2	0.05	44	400	2.417	9266.4	1.168	52%	9.134	1.310	46%
3	0.1	44	200	1.917	9266.4	1.168	39%	9.134	1.310	32%
4	0.2	44	100	2.333	9266.4	1.168	50%	9.134	1.310	44%
5	0.8	44	25	1.917	4633.2	1.168	39%	9.134	1.310	32%

7.5 Conclusion

Data collected in the current study has been compared and integrated with existing relevant literature resulting in consolidated body of literature characterizing the frequency responses of VIMS across different stimuli amplitude, stimuli velocity, axis of motion and FOVs. To our delighted, in addition to the proofing of the 'two-frequency-response hypothesis' that has been the main objective of our thesis, two other new and origin findings are discovered. First, unlike So *et al.* (2001a), the relationship between nausea and SV was found to be non-linear. Secondly, the log-CSDV model was found to provide comparable prediction with the velocity-weighted CSDV model as proposed in So *et al.* (2001a).

CHAPTER 8: CONCLUSIONS, LIMITATIONS, AND FUTURE WORK

8.1 Conclusions

In this thesis, frequency-dependence characteristics of visually induced motion sickness (VIMS), illusions of self-motion (vection), and perceived speed (PS) have been investigated in four empirical experiments under conditions in which stimuli's velocity and stimuli's amplitude were in isolation to manipulate stimuli's frequency.

Two distinctive frequency responses, depending on whether the velocity or amplitude of the stimuli is isolated, have been consistently identified for VIMS, vection, and PS under conditions with two different scenes oscillating along fore-and-aft axis. These findings are important because these two patterns of frequency responses are both referred to as one type in the current literature. This research helps to alert researchers the need to be aware of such distinctive discrepancy in frequency responses. Discussion on how the current findings are integrated with the existing literature and models of VIMS can be founded in Chapter 7.

The main findings and contributions of the thesis are listed below:

- When keeping stimuli's velocity constant, changing amplitude (hence, frequency) does not significantly affect levels of VIMS as measured by rated nausea, simulator sickness questionnaire (SSQ) scores. Frequency responses of VIMS have been founded to be flat within the range from 0.0125 Hz to 3.2 Hz with two commonly used patterns (radial checker-board pattern and star-field pattern). This new and original fining contradicts with two previous studies and reasons have been discussed.

- When stimuli's amplitude was fixed, levels of VIMS (both nausea and SSQ scores) were significantly affected by velocity (hence, frequency). An increase-peak-reduce trend of frequency responses of VIMS has been identified. The frequency at which VIMS will peak increase with increasing stimuli's amplitude. Although the results are consistent with two previous studies, the finding is new and original because in both past studies, the frequency response was not specifically labeled and reported as velocity-manipulated frequency responses. When integrated with the existing body of literature, these new and original findings are likely to be generalized to situations with visual oscillations in both translational and rotational axes as well as with different FOVs.

- The above two findings support the 'two-frequency-response hypothesis' which predicts the existence of two different frequency responses in vection and VIMS when frequency was manipulated by changing velocity alone or changing amplitude alone. This is a new and original finding.

- The use of percentage likelihood graph has been demonstrated. This method can be a new and concise method to unify and visualize the two types of frequency responses for VIMS (or vection) on a single graph. It can also be a useful reference tool for display/movie/video game designers to make decisions on the relative levels of velocity, frequency, and amplitude of the visual motions so as to balance between levels of VIMS and vection. The current IWA3 documents related to VIMS published by the International Standardization Organization (ISO) does not contain such information. This thesis proposes that the likelihood graph for vection and VIMS should be included in future standards. Although the % likelihood graph has been widely applied in the field of physically induced motion sickness, this is the first time the % likelihood graph is applied to vection and VIMS.

- Contrary to previous finding in So *et al.* (2001a), the thesis reports a non-linear relationship between VIMS and spatial velocity (SV). This is new and original.

- Using data collected in this study, a new velocity weighted and a new logarithmic transformed cybersickness dose value (CSDV) models have been developed. Both models are new and have been shown to be able to predict levels of VIMS with errors ranging from 1% to 23% with a median error level of 4%. This is the first time the CSDV was used to predict levels of VIMS. In the past, CSDV has only been used to describe the VIMS data.

8.2 Limitations

Despite of the significance and importance of the current findings, there are some possible limitations:

- Only young participants (age between 18 to 30) were included in the current study. Since it has been suggested that VIMS severity can be affected by the ages of individuals, the current results may not generalize to other populations, such as older people or children.
- Only abstract virtual scenes were adopted in the current study. It could be beneficial to measure VIMS with the use of visual scenes that composed of familiar objects in real world, since one of the major applications of the current findings would be associated with designs of movie/game contents, which often involve complicated scenes rather than simple stripes or dots. Nonetheless, some of our results are consistent with the findings of Chen (2006) who used a virtual environment constructed using captured pictures of the real world. Furthermore, the current findings have been tested to be consistent with two type visual patterns.
- Only visual motions along fore-and-aft axis were investigated. However, evidence have been reported in Chen (2006) whose results are consistent with some of our findings that the general shape of frequency response of VIMS are similar when axis of motion changed from fore-and-aft to lateral, yaw axes.
- Only sinusoidal waveform motions were explored in the current study. It is acknowledged that motion patterns in video games or movies are seldom pure sinusoidal oscillations. As our findings have been shown to be consistent with So *et al.* (2001a) who used realistic navigation motion in six axes, we hypothesize that the results can be generalizable. Of course, future work is needed to confirm that.

8.3 Future work

Based on the current findings, the following future studies are recommended:

- It is worth to further elaborate the percentage likelihood graphs for VIMS and vection for the sake of its promising industrial applications. Higher resolution of the likelihood graph is desirable. Also a series of these likelihood graphs that account for other stimuli variables, e.g. axis of motion, FOV, scene complexity, are valuable.

- Further studies to develop the CSDV model are urged.

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APPENDIX 3.1: 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** [1] **Female** [2]

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					
	t	0	1	2	3

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					
	t	0	1	2	3

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

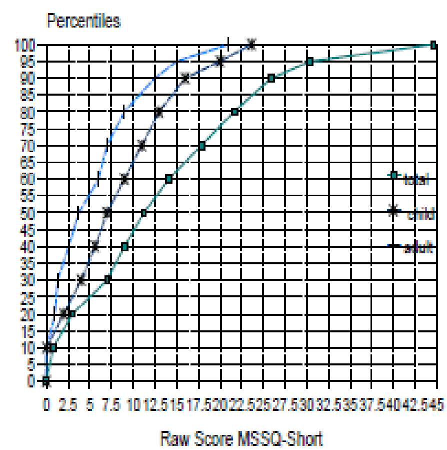


Figure: Cumulative distribution Percentiles of the Raw Scores of the MSSQ-Short (n=257 subjects).

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 3.2: Pre-exposure and Post-exposure Simulator Sickness Questionnaires (SSQ) (adopted from Kennedy *et al.*, 1993)

SYMPTOM CHECKLIST (Pre-exposure)

Pre-exposure instruction: 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)

SYMPTOM CHECKLIST (Post-exposure)

Pre-exposure instruction: 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)

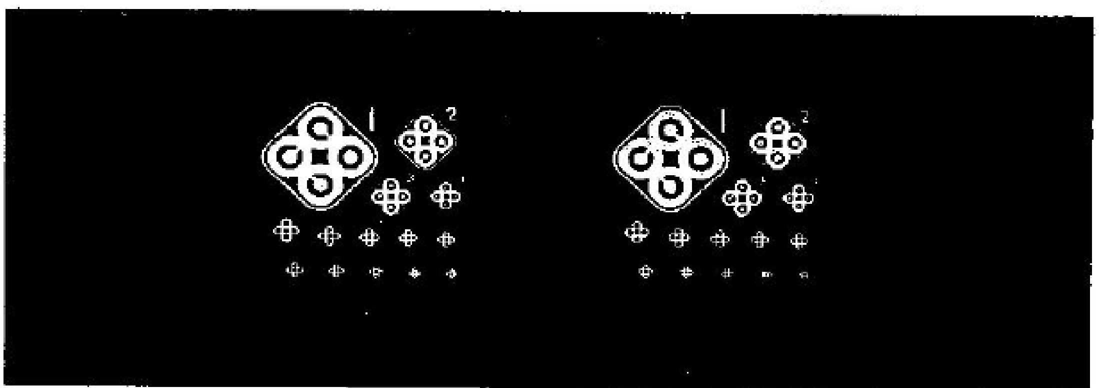
APPENDIX 3.3: Instructions of Measuring Visual Acuity at Near Point by an "Optec®2000" Visual Tester (adopted from Stereo Optical Corp.)

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 4.1: Results of Wilcoxon Signed Rank Test - Effects of Frequencies on Perceived Speed (PS) under Constant r.m.s. Velocities For Experiment PS1 and PS2

Note: tuples which are shaded indicate statistical significance. The first number in each tuple is the Z value and the second is the p value of the Wilcoxon Signed Rank test (IBM SPSS Statistics 21).

Exp.PS1 - **Perceived Speed** - Results of Wilcoxon Signed Rank Test								
		Keep r.m.s. Velocity Constant						
Freq1	Freq2	Vel=5.6 m/s	Vel=11 m/s	Vel=22 m/s	Vel=44 m/s	Vel=89 m/s	Vel=178 m/s	Vel=356 m/s
0.025 Hz	0.0125 Hz		-0.952					
			0.341					
0.05 Hz	0.0125 Hz		-1.965					
			0.049					
0.1 Hz	0.0125 Hz		-2.721					
			0.007					
0.2 Hz	0.0125 Hz		-2.708					
			0.007					
0.4 Hz	0.0125 Hz		-2.812					
			0.005					
0.8 Hz	0.0125 Hz		-2.805					
			0.005					
1.6 Hz	0.0125 Hz							
3.2 Hz	0.0125 Hz							
0.05 Hz	0.025 Hz		-1.862	-0.922				
			0.063	0.357				
0.1 Hz	0.025 Hz		-2.823	-1.79				
			0.005	0.074				
0.2 Hz	0.025 Hz		-2.814	-1.893				
			0.005	0.058				
0.4 Hz	0.025 Hz		-2.821	-2.397				
			0.005	0.017				
0.8 Hz	0.025 Hz		-2.805	-2.805				
			0.005	0.005				
1.6 Hz	0.025 Hz							
3.2 Hz	0.025 Hz							
0.1 Hz	0.05 Hz	-1.807	-1.983	-2.555	-2.585	-0.302	-2.414	
		0.071	0.047	0.011	0.01	0.763	0.016	
0.2 Hz	0.05 Hz		-2.615	-2.825	-2.399	-1.223	-0.597	
			0.009	0.005	0.016	0.221	0.551	
0.4 Hz	0.05 Hz		-2.673	-2.694	-2.254	-1.543	-1.743	
			0.008	0.007	0.024	0.123	0.081	
0.8 Hz	0.05 Hz		-2.67	-2.675	-2.812	-1.071	-0.923	
			0.008	0.007	0.005	0.284	0.356	
1.6 Hz	0.05 Hz					-1.304	-0.418	
						0.192	0.676	
3.2 Hz	0.05 Hz						-1.794	
							0.073	
0.2 Hz	0.1 Hz		-2.157	-2.414	-0.828	-0.736	-1.513	
			0.031	0.016	0.408	0.461	0.13	
0.4 Hz	0.1 Hz		-2.677	-2.263	-0.954	-1.651	0	
			0.007	0.024	0.34	0.099	1	
0.8 Hz	0.1 Hz		-2.655	-2.558	-2.536	-1.725	-0.851	
			0.008	0.011	0.011	0.084	0.395	

(Cont.) Exp.PS1 - **Perceived Speed** - Results of Wilcoxon Signed Rank Test								
		Keep r.m.s. Velocity Constant						
Freq1	Freq2	Vel=5.6 m/s	Vel=11 m/s	Vel=22 m/s	Vel=44 m/s	Vel=89 m/s	Vel=178 m/s	Vel=356 m/s
1.6 Hz	0.1 Hz					-1.727	-1.136	
						0.084	0.256	
3.2 Hz	0.1 Hz						-0.714	
							0.475	
0.4 Hz	0.2 Hz		-1.895	-1.425	-0.447	-1.518	-0.99	
			0.058	0.154	0.655	0.129	0.322	
0.8 Hz	0.2 Hz		-2.49	-1.963	-2.428	-1.084	-0.424	
			0.013	0.05	0.015	0.279	0.671	
1.6 Hz	0.2 Hz					-1.902	-0.171	
						0.057	0.865	
3.2 Hz	0.2 Hz						-1.429	
							0.153	
0.8 Hz	0.4 Hz		-2.176	-2.132	-2.401	-0.171	-0.422	-1.823
			0.03	0.033	0.016	0.865	0.673	0.068
1.6 Hz	0.4 Hz					-1.138	-0.851	
						0.255	0.395	
3.2 Hz	0.4 Hz						-0.772	
							0.44	
1.6 Hz	0.8 Hz					-0.982	-0.849	
						0.326	0.396	
3.2 Hz	0.8 Hz						-1.136	
							0.256	
3.2 Hz	1.6 Hz						-2.094	
							0.036	

Exp.PS2 - Perceived Speed - Results of Wilcoxon Signed Rank Test				
		Keep r.m.s. Velocity Constant		
Freq.1	Freq.2	Vel=5.6 m/s	Vel=22 m/s	Vel=89 m/s
0.05 Hz	0.0125 Hz	-3.296		
		0.001		
0.2 Hz	0.0125 Hz	-3.409		
		0.001		
0.1 Hz	0.05 Hz		-2.763	
			0.006	
0.2 Hz	0.05 Hz	-2.642	-1.538	
		0.008	0.124	
0.4 Hz	0.05 Hz		-2.512	
			0.012	
0.8 Hz	0.05 Hz		-2.354	
			0.019	
0.2 Hz	0.1 Hz		-0.126	
			0.9	
0.4 Hz	0.1 Hz		-1.728	
			0.084	
0.8 Hz	0.1 Hz		-2.166	
			0.03	
0.4 Hz	0.2 Hz		-2.201	
			0.028	
0.8 Hz	0.2 Hz		-2.291	-1.957
			0.022	0.05
3.2 Hz	0.2 Hz			-0.795
				0.426
0.8 Hz	0.4 Hz		-2.103	
			0.035	
3.2 Hz	0.8 Hz			-0.471
				0.638

APPENDIX 4.2: Results of Wilcoxon Signed Rank Test - Effects of Frequencies on Perceived Speed (PS) under Constant Amplitudes For Experiment PS1 and PS2

Exp.PS1 - **Perceived Speed** - Results of Wilcoxon Signed Rank Test								
		Keep Amplitude Constant						
Freq1	Freq2	Amp=6.25m	Amp=12.5m	Amp=25m	Amp=50m	Amp=100m	Amp=200m	Amp=400m
0.025 Hz	0.0125 Hz						-2.673	
							0.008	
0.05 Hz	0.0125 Hz						-2.807	
							0.005	
0.1 Hz	0.0125 Hz						-2.807	
							0.005	
0.2 Hz	0.0125 Hz						-2.805	
							0.005	
0.4 Hz	0.0125 Hz						-2.807	
							0.005	
0.8 Hz	0.0125 Hz						-2.807	
							0.005	
1.6 Hz	0.0125 Hz							
3.2 Hz	0.0125 Hz							
0.05 Hz	0.025 Hz					-2.825	-2.809	
						0.005	0.005	
0.1 Hz	0.025 Hz					-2.812	-2.807	
						0.005	0.005	
0.2 Hz	0.025 Hz					-2.807	-2.805	
						0.005	0.005	
0.4 Hz	0.025 Hz					-2.805	-2.805	
						0.005	0.005	
0.8 Hz	0.025 Hz					-2.807	-2.809	
						0.005	0.005	
1.6 Hz	0.025 Hz							
3.2 Hz	0.025 Hz							
0.1 Hz	0.05 Hz		-2.716	-2.840	-2.684	-2.814	-2.812	-2.805
			0.007	0.005	0.007	0.005	0.005	0.005
0.2 Hz	0.05 Hz		-2.829	-2.812	-2.850	-2.814	-2.805	
			0.005	0.005	0.004	0.005	0.005	
0.4 Hz	0.05 Hz		-2.820	-2.825	-2.816	-2.807	-2.807	
			0.005	0.005	0.005	0.005	0.005	
0.8 Hz	0.05 Hz		-2.825	-2.807	-2.812	-2.812	-2.807	
			0.005	0.005	0.005	0.005	0.005	
1.6 Hz	0.05 Hz		-2.814	-2.810				
			0.005	0.005				
3.2 Hz	0.05 Hz		-2.820					
			0.005					
0.2 Hz	0.1 Hz		-2.692	-2.829	-2.848	-2.814	-2.812	
			0.007	0.005	0.004	0.005	0.005	
0.4 Hz	0.1 Hz		-2.807	-2.829	-2.821	-2.805	-2.809	
			0.005	0.005	0.005	0.005	0.005	
0.8 Hz	0.1 Hz		-2.809	-2.805	-2.807	-2.810	-2.814	
			0.005	0.005	0.005	0.005	0.005	

(Cont.) Exp.PS1 - **Perceived Speed** - Results of Wilcoxon Signed Rank Test								
		Keep Amplitude Constant						
Freq1	Freq2	Amp=6.25m	Amp=12.5m	Amp=25m	Amp=50m	Amp=100m	Amp=200m	Amp=400m
1.6 Hz	0.1 Hz		-2.805	-2.805				
			0.005	0.005				
3.2 Hz	0.1 Hz		-2.807					
			0.005					
0.4 Hz	0.2 Hz		-2.809	-2.724	-2.877	-2.670	-2.823	
			0.005	0.006	0.004	0.008	0.005	
0.8 Hz	0.2 Hz		-2.805	-2.809	-2.840	-2.821	-2.809	
			0.005	0.005	0.005	0.005	0.005	
1.6 Hz	0.2 Hz		-2.805	-2.807				
			0.005	0.005				
3.2 Hz	0.2 Hz		-2.807					
			0.005					
0.8 Hz	0.4 Hz	-2.524	-2.692	-2.825	-2.684	-2.814	-2.680	
		0.012	0.007	0.005	0.007	0.005	0.007	
1.6 Hz	0.4 Hz		-2.807	-2.812				
			0.005	0.005				
3.2 Hz	0.4 Hz		-2.807					
			0.005					
1.6 Hz	0.8 Hz		-2.316	-2.677				
			0.021	0.007				
3.2 Hz	0.8 Hz		-2.810					
			0.005					
3.2 Hz	1.6 Hz		-2.809					
			0.005					

Exp.PS2 - Perceived Speed - Results of Wilcoxon Signed Rank Test				
		Keep Amplitude Constant		
Freq.1	Freq.2	Amp=6.25m	Amp=25m	Amp=100m
0.05 Hz	0.0125 Hz			-3.408
				0.001
0.2 Hz	0.0125 Hz			-3.408
				0.001
0.1 Hz	0.05 Hz		-2.898	
			0.004	
0.2 Hz	0.05 Hz		-3.411	-3.408
			0.001	0.001
0.4 Hz	0.05 Hz		-3.408	
			0.001	
0.8 Hz	0.05 Hz		-3.408	
			0.001	
0.2 Hz	0.1 Hz		-3.409	
			0.001	
0.4 Hz	0.1 Hz		-3.408	
			0.001	
0.8 Hz	0.1 Hz		-3.408	
			0.001	
0.4 Hz	0.2 Hz		-3.408	
			0.001	
0.8 Hz	0.2 Hz	-3.408	-3.408	
		0.001	0.001	
3.2 Hz	0.2 Hz	-3.408		
		0.001		
0.8 Hz	0.4 Hz		-3.408	
			0.001	
3.2 Hz	0.8 Hz	-3.408		
		0.001		

APPENDIX 4.3: Results of Wilcoxon Signed Rank Test - Effects of Frequencies on Vection under Constant r.m.s. Velocities For Experiment PS1 and PS2

		Exp.PS1 - **Vection** - Results of Wilcoxon Signed Rank Test						
		Keep RMS Velocity Constant						
Freq1	Freq2	Vel=5.6 m/s	Vel=11 m/s	Vel=22 m/s	Vel=44 m/s	Vel=89 m/s	Vel=178 m/s	Vel=356 m/s
0.025 Hz	0.0125 Hz		-1.633					
			0.102					
0.05 Hz	0.0125 Hz		-1.134					
			0.257					
0.1 Hz	0.0125 Hz		-0.378					
			0.705					
0.2 Hz	0.0125 Hz		-1.134					
			0.257					
0.4 Hz	0.0125 Hz		-1.890					
			0.059					
0.8 Hz	0.0125 Hz		-1.890					
			0.059					
1.6 Hz	0.0125 Hz							
3.2 Hz	0.0125 Hz							
0.05 Hz	0.025 Hz		-1.000	-1.633				
			0.317	0.102				
0.1 Hz	0.025 Hz		-1.604	-1.633				
			0.109	0.102				
0.2 Hz	0.025 Hz		-1.633	-1.625				
			0.102	0.104				
0.4 Hz	0.025 Hz		-2.041	-1.930				
			0.041	0.054				
0.8 Hz	0.025 Hz		-2.041	-1.706				
			0.041	0.088				
1.6 Hz	0.025 Hz							
3.2 Hz	0.025 Hz							
0.1 Hz	0.05 Hz	-0.447	-1.633	-0.577	0.000	-1.414	-0.378	
		0.655	0.102	0.564	1.000	0.157	0.705	
0.2 Hz	0.05 Hz		-1.633	-1.289	-1.089	-1.994	-1.414	
			0.102	0.197	0.276	0.046	0.157	
0.4 Hz	0.05 Hz		-2.041	-1.403	-1.807	-1.063	-1.549	
			0.041	0.161	0.071	0.288	0.121	
0.8 Hz	0.05 Hz		-2.041	-1.382	-1.275	-1.807	-1.980	
			0.041	0.167	0.202	0.071	0.048	
1.6 Hz	0.05 Hz					-1.913	-2.038	
						0.056	0.042	
3.2 Hz	0.05 Hz						-1.612	
							0.107	
0.2 Hz	0.1 Hz		-1.000	-1.414	-1.089	-1.633	-1.134	
			0.317	0.157	0.276	0.102	0.257	
0.4 Hz	0.1 Hz		-1.633	-1.667	-1.633	-0.649	-1.292	
			0.102	0.096	0.102	0.516	0.196	
0.8 Hz	0.1 Hz		-1.633	-1.406	-1.265	-1.933	-1.980	
			0.102	0.160	0.206	0.053	0.048	

(Cont.) Exp.PS1 - **Vection** - Results of Wilcoxon Signed Rank Test								
		Keep RMS Velocity Constant						
Freq1	Freq2	Vel=5.6 m/s	Vel=11 m/s	Vel=22 m/s	Vel=44 m/s	Vel=89 m/s	Vel=178 m/s	Vel=356 m/s
1.6 Hz	0.1 Hz					-1.876	-1.974	
						0.061	0.048	
3.2 Hz	0.1 Hz						-1.438	
							0.150	
0.4 Hz	0.2 Hz		-1.414	-0.577	-1.857	-0.632	-0.962	
			0.157	0.564	0.063	0.527	0.336	
0.8 Hz	0.2 Hz		-1.414	-0.447	-0.970	-1.403	-1.552	
			0.157	0.655	0.332	0.161	0.121	
1.6 Hz	0.2 Hz					-1.294	-1.703	
						0.196	0.088	
3.2 Hz	0.2 Hz						-1.191	
							0.234	
0.8 Hz	0.4 Hz		0.000	0.000	-0.137	-2.251	-0.879	-1.300
			1.000	1.000	0.891	0.024	0.380	0.194
1.6 Hz	0.4 Hz					-2.251	-1.867	
						0.024	0.062	
3.2 Hz	0.4 Hz						-1.141	
							0.254	
1.6 Hz	0.8 Hz					0.000	-1.131	
						1.000	0.258	
3.2 Hz	0.8 Hz						-0.782	
							0.434	
3.2 Hz	1.6 Hz						-0.302	
							0.763	

Exp.PS2 - Vection - Results of Wilcoxon Signed Rank Test				
		Keep r.m.s. Velocity Constant		
Freq.1	Freq.2	Vel=5.6 m/s	Vel=22 m/s	Vel=89 m/s
0.05 Hz	0.0125 Hz	-1.381		
		0.167		
0.2 Hz	0.0125 Hz	-2.197		
		0.028		
0.1 Hz	0.05 Hz		-0.633	
			0.526	
0.2 Hz	0.05 Hz	-2.105	-1.259	
		0.035	0.208	
0.4 Hz	0.05 Hz		-0.786	
			0.432	
0.8 Hz	0.05 Hz		-1.748	
			0.08	
0.2 Hz	0.1 Hz		-0.804	
			0.421	
0.4 Hz	0.1 Hz		-0.785	
			0.432	
0.8 Hz	0.1 Hz		-1.508	
			0.131	
0.4 Hz	0.2 Hz		-0.472	
			0.637	
0.8 Hz	0.2 Hz		-1.493	-2.174
			0.135	0.03
3.2 Hz	0.2 Hz			-2.387
				0.017
0.8 Hz	0.4 Hz		-1.157	
			0.247	
3.2 Hz	0.8 Hz			-1.905
				0.057

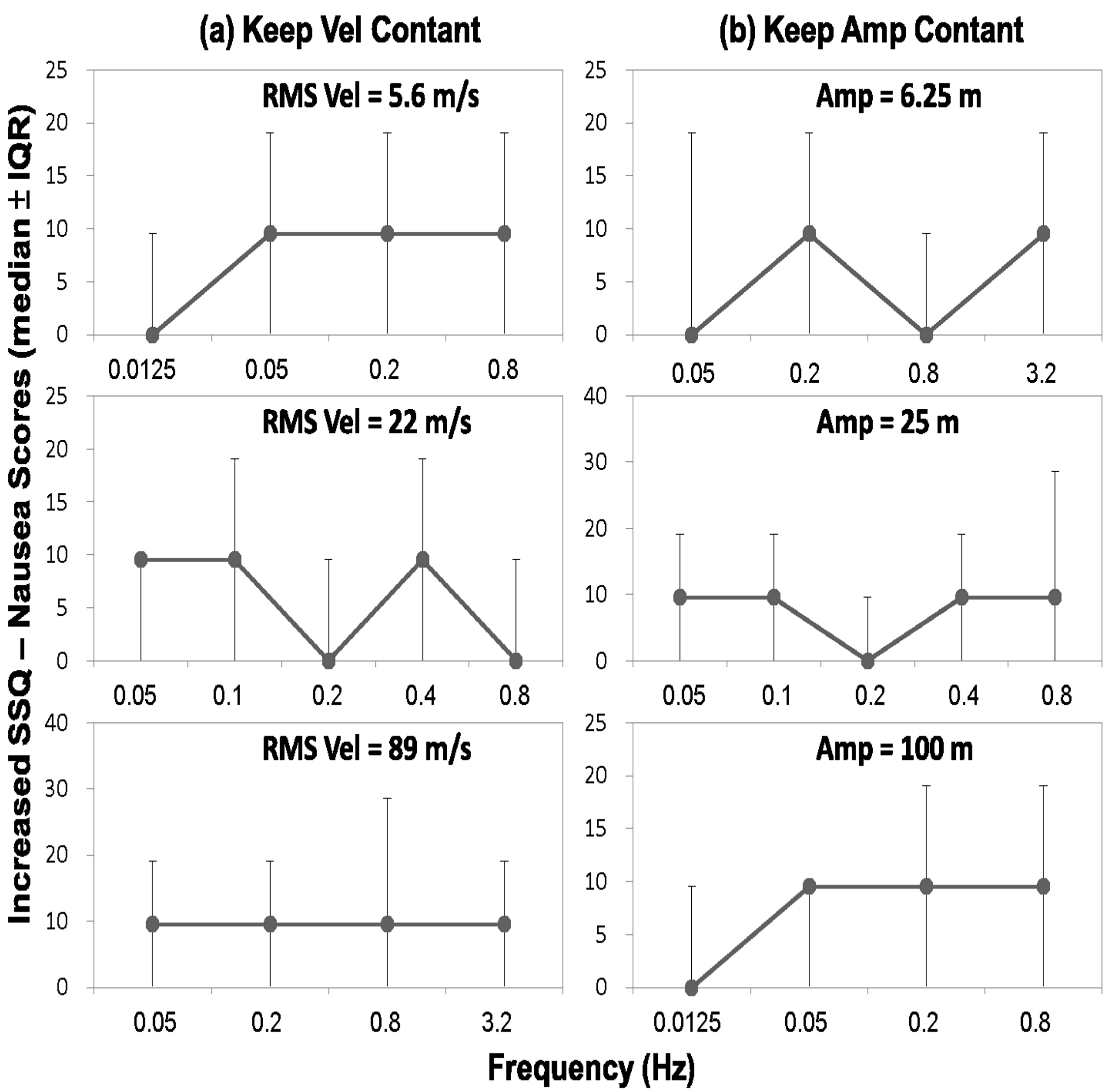
APPENDIX 4.4: Results of Wilcoxon Signed Rank Test - Effects of Frequencies on Vection under Constant Amplitudes For Experiment PS1 and PS2

Exp.PS1 - **Vection** - Results of Wilcoxon Signed Rank Test								
		Keep Amplitude Constant						
Freq1	Freq2	Amp=6.25m	Amp=12.5m	Amp=25m	Amp=50m	Amp=100m	Amp=200m	Amp=400m
0.025 Hz	0.0125 Hz						-2.251	
							0.024	
0.05 Hz	0.0125 Hz						-2.264	
							0.024	
0.1 Hz	0.0125 Hz						-2.539	
							0.011	
0.2 Hz	0.0125 Hz						-2.539	
							0.011	
0.4 Hz	0.0125 Hz						-2.662	
							0.008	
0.8 Hz	0.0125 Hz						-2.661	
							0.008	
1.6 Hz	0.0125 Hz							
3.2 Hz	0.0125 Hz							
0.05 Hz	0.025 Hz					-0.577	-0.378	
						0.564	0.705	
0.1 Hz	0.025 Hz					-2.070	-2.041	
						0.038	0.041	
0.2 Hz	0.025 Hz					-2.232	-2.114	
						0.026	0.034	
0.4 Hz	0.025 Hz					-2.316	-2.095	
						0.021	0.036	
0.8 Hz	0.025 Hz					-2.210	-2.161	
						0.027	0.031	
1.6 Hz	0.025 Hz							
3.2 Hz	0.025 Hz							
0.1 Hz	0.05 Hz		-1.342	-1.000	-0.378	-1.857	-2.070	-1.913
			0.180	0.317	0.705	0.063	0.038	0.056
0.2 Hz	0.05 Hz		-0.816	-0.966	-1.512	-2.530	-1.615	
			0.414	0.334	0.131	0.011	0.106	
0.4 Hz	0.05 Hz		-1.667	-1.089	-2.132	-2.172	-1.612	
			0.096	0.276	0.033	0.030	0.107	
0.8 Hz	0.05 Hz		-1.841	-2.333	-1.880	-2.109	-1.608	
			0.066	0.020	0.060	0.035	0.108	
1.6 Hz	0.05 Hz		-2.060	-2.555				
			0.039	0.011				
3.2 Hz	0.05 Hz		-2.375					
			0.018					
0.2 Hz	0.1 Hz		-1.000	-0.557	-2.000	-1.342	-1.628	
			0.317	0.577	0.046	0.180	0.103	
0.4 Hz	0.1 Hz		-1.000	-0.966	-2.401	-1.257	-1.684	
			0.317	0.334	0.016	0.209	0.092	
0.8 Hz	0.1 Hz		-1.342	-2.121	-2.105	-1.508	-1.651	
			0.180	0.034	0.035	0.132	0.099	

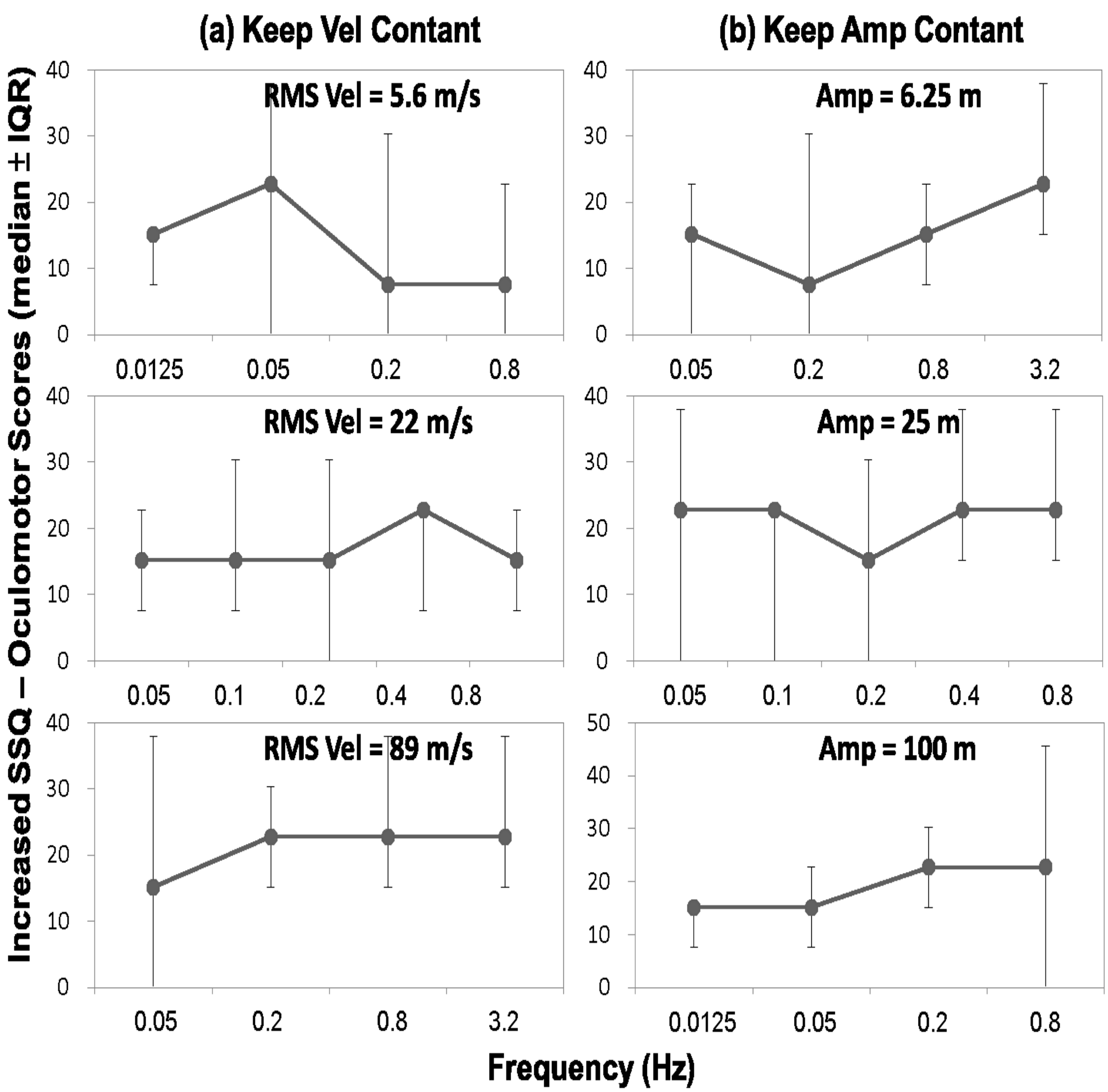
(Cont.) Exp.PS1 - **Vection** - Results of Wilcoxon Signed Rank Test								
		Keep Amplitude Constant						
Freq1	Freq2	Amp=6.25m	Amp=12.5m	Amp=25m	Amp=50m	Amp=100m	Amp=200m	Amp=400m
1.6 Hz	0.1 Hz		-2.041	-2.342				
			0.041	0.019				
3.2 Hz	0.1 Hz		-2.038					
			0.042					
0.4 Hz	0.2 Hz		-1.732	-0.743	-2.070	-1.021	-1.406	
			0.083	0.458	0.038	0.307	0.160	
0.8 Hz	0.2 Hz		-1.604	-1.823	-1.298	-1.398	-1.561	
			0.109	0.068	0.194	0.162	0.119	
1.6 Hz	0.2 Hz		-2.232	-2.280				
			0.026	0.023				
3.2 Hz	0.2 Hz		-2.113					
			0.035					
0.8 Hz	0.4 Hz	-1.890	-1.134	-1.131	-0.541	-1.518	-1.000	
		0.059	0.257	0.258	0.589	0.129	0.317	
1.6 Hz	0.4 Hz		-1.930	-1.681				
			0.054	0.093				
3.2 Hz	0.4 Hz		-2.030					
			0.042					
1.6 Hz	0.8 Hz		-1.518	-1.730				
			0.129	0.084				
3.2 Hz	0.8 Hz		-1.912					
			0.056					
3.2 Hz	1.6 Hz		-1.282					
			0.200					

Exp.PS2 - Vection - Results of Wilcoxon Signed Rank Test				
		Keep Amplitude Constant		
Freq.1	Freq.2	Amp=6.25m	Amp=25m	Amp=100m
0.05 Hz	0.0125 Hz			-2.272
				0.023
0.2 Hz	0.0125 Hz			-2.756
				0.006
0.1 Hz	0.05 Hz		-2.806	
			0.005	
0.2 Hz	0.05 Hz		-2.587	-2.903
			0.01	0.004
0.4 Hz	0.05 Hz		-3.182	
			0.001	
0.8 Hz	0.05 Hz		-2.835	
			0.005	
0.2 Hz	0.1 Hz		-2.303	
			0.021	
0.4 Hz	0.1 Hz		-3.015	
			0.003	
0.8 Hz	0.1 Hz		-2.552	
			0.011	
0.4 Hz	0.2 Hz		-3.084	
			0.002	
0.8 Hz	0.2 Hz	-2.748	-2.105	
		0.006	0.035	
3.2 Hz	0.2 Hz	-1.696		
		0.09		
0.8 Hz	0.4 Hz		-0.711	
			0.477	
3.2 Hz	0.8 Hz	-0.37		
		0.712		

APPENDIX 5.1: Frequency Responses of SSQ Sub-Scores - Nausea Scores



APPENDIX 5.2: Frequency Responses of SSQ Sub-Scores - Oculomotor Scores



APPENDIX 5.3: Frequency Responses of SSQ Sub-Scores - Disorientation Scores