Effects of eye motion, foveal retinal slip and peripheral retinal slip on visually induced motion sickness

by

GUO, Cuiting

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

Jan 2014, Hong Kong

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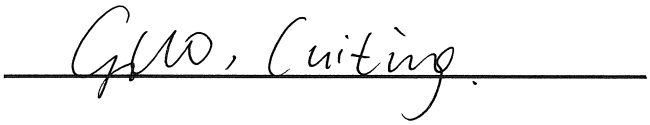

GUO, Cuiting

14 January 2014

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This is to certify that I have examined the above PhD thesis
and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by
the thesis examination committee have been made.

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14 January 2014

Acknowledgements

I would like to express my grateful gratitude to my supervisor Prof. Richard H. Y. So for his support, guidance, advice and continuous encouragement during the whole research.

Deep appreciation is expressed to Prof. Fugee TSUNG, Prof. QI, Xiangtong, Prof. Andrew Horner, Prof. Kiryu Tohru for giving me advice during the defense examination and Prof. Ravi Goonetilleke for giving me advise during human factor seminars.

Thanks are extended to all the subjects for participating my experiments. You are all great subjects and without your help I cannot finish these experiments.

Finally, I would like to thank my parents and friends in HKUST for their warm mental support and encouragement during the frustration period of the experiments.

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Abstract

Motions of visual images projected on the retina (referred to as retinal slips) are essential for provoking vection (illusion of self-motion) and visually induced motion sickness (VIMS) (Brandt, 1973). These projected image motions can be classified into: (i) peripheral retinal slip (PRS) and (ii) foveal retinal slip (FRS). Both PRS and FRS are modulated by eye motion (EM). Eye motion (EM) has also been found to play a crucial role in causing visually induced motion sickness (VIMS) (Ebenholtz *et al.*, 1994). In past studies, effects of EM were confounded with FRS or PRS. Empirical study on the isolated effects of EM, FRS and PRS on VIMS could not be found.

This thesis reports a series of studies evaluating the isolated effects of EM velocity (EMv), PRS velocity (PRSv) and FRS velocity (FRSv) on VIMS. In Experiment one, effects of EMv and FRSv on VIMS were evaluated under controlled PRSv. In Experiment two, effects of PRSv on VIMS under controlled EMv (40dps) was examined. Results showed that (i)

increasing FRSv from 0dps to 15dps during occurrence of EM significantly increased VIMS ($p<0.005$); (ii) reduction of EMv during occurrence of FRS significantly reduced VIMS ($p<0.01$); and (iii) increasing PRSv from 10dps to 60dps increases the mean value of VIMS but the effect was not significant when EMv was controlled at 40dps. Experiments three and four studied the role of EM on VIMS among computer game players. Results showed that (i) reducing EMv could reduce VIMS during passive watching; (ii) active playing and passive watching did not result in different EMv; and (iii) the use of an eye fixation marker did not reduce EMv during active game playing.

The last part of the thesis focuses on modeling the relative contributions of EMv, PRSv and FRSv on VIMS. Results of regression analyses showed that all three predictor variables had significant main effects towards VIMS and the model R-sq was 97%. Further conclusion and discussion are presented in this thesis.

Chapter 1 Introduction

1.1 Visually induced motion sickness (VIMS)

Motion sickness is a general term for a constellation of symptoms and signs due to exposure to abrupt, periodic, or unnatural accelerations (Kennedy, 1986). Common symptoms of motion sickness include nausea, sweating, dizziness, disorientation, vomiting, etc. The severity and types of syndromes of motion sickness vary with individual, type and duration of motion stimulus. Many daily life situations can produce motion sickness, such as riding in a boat, car and swing. Some special or laboratory situations can also provoke motion sickness, such as traveling in a zero gravity aircraft (Kellogg, 1965), exposure to a rotating room (Graybiel, 1965), vertical oscillator (Guignard, 1982) and optokinetic stimulations. In general, about one-third of Hong Kong Chinese are susceptible to motion sickness (So *et al.*, 1999).

Visually induced motion sickness (VIMS) is named by its major causes – visual. It is a general category of motion sickness provoked by virtual environment. It is seen among people during playing some types of computer game, for example, first person shooting game, mirror edge. It is also normally seen when people watch large screen movie, e.g., IMAX. Incidences of VIMS occurring in the users of virtual environments have been reported (Hettinger and Riccio, 1992; Ji *et al.,* 2009; Kiryu and So, 2007; So and Ujike, 2010; Ujike, 2008). Commonly used stimulus of VIMS is the optokinetic drum with its inner part drawn in alternative black and white strips. Since the occurrence of VIMS can reduce the efficacy, safety and usability of VE technology (Biocca, 1992), it would be useful to study the factors by which VIMS is provoked and use these factors to predict motion sickness when designing VE. In 2007, a special conference on VIMS was held to enable international experts to exchange their knowledge (So *et al.*, 2007). Selected papers have been published as a special issue in Applied Ergonomics (So and Uijike, 2010).

It is easy to construct an environment to provoke VIMS, but the internal mechanism of VIMS is still understudied (Ji *et al.,* 2005). It was early explained as a result of inharmony in the control of body motion. Human central nervous system (CNS) generates commands on muscles to control body motion using sensory feedback from eyes, inner ears and somatosensory organs. Human eye is responsible for sensation of velocity and position, and

inner ears as the main composition of human vestibular system, is responsible for sensation of motion and spatial orientation to keep body in balance. Normally the integration of visual and vestibular system works perfectly in controlling body motion for a healthy person, while in some unnatural circumstances, e.g., ship, car, or some virtual reality environment, an error signal generated from the discrepancy between these two systems is sent to CNS, which afterwards produces symptoms of motion sickness. How is this discrepancy generated? There are generally three categories of conflict. The first category is lack of visually indication motion when human body is actually in a motion. Suppose you are sitting in a moving car without looking outside: you receive a vestibular feedback corresponding to the actual pattern of car movement, but since you can only see the inside of the car, the visual feedback indicates that there is no movement. The second category is lack of vestibular indication of motion, or in a more accurate way we say, visual system generates an illusory motion indication while actually vestibular system dose not sense any. Suppose you are cycling, normally you will not get sick because visual and vestibular motion signals consistent with each other. However, if you wear a Google glass and record what you have seen during cycling, and after that plays the video to a person sitting still, this person may get sick. The third category is that both visual and vestibular system receives motion signals, but inconsistency or latency occurs. Studies show that processing time between visual and vestibular system are different (Barnett, 2009). It is also said that anticipation or known of next step of motion can help reduce motion sickness. This may explains why drivers generally experience much less motion sickness than passenger. Explanation on the genesis of motion sickness through integration of visual and vestibular system above belongs to a widely accepted theory called sensory conflict theory. Details of this theory are reviewed in next part, and other theories related to motion sickness are also reviewed.

1.2 Terminology

Major terminologies and their abbreviations as well as explanations used in this thesis are listed in Table 1. More detailed introduction will be presented in chapter two.

Table 1: Terminology table

Terms	Abbreviations	Explanations
Visually induced motion sickness	VIMS	Motion sickness induced by visual stimuli
Optokinetic nystagmus	OKN	Periodic eye motion provoked by prolong and large field of view visual stimuli
Degree per second	dps	Unit used to describe velocities of visual motion, eye motion, etc.
Slow phase velocity	SPV	Velocity of slow phase of one OKN cycle
Eye motion velocity	EMv	In cases where eye motion is OKN, it is defined as SPV; in cases where eye motion is general types, it is defined as the distance in degree of eye motion in one second.
Foveal reinal slip velocity	FRSv	The projected velocity of visual target to the central retina
Peripheral retinal slip velocity	PRSv	The projected velocity of visual stimuli to the peripheral retina

Chapter 2 Literature review

2.1 Sensory conflict theory

Sensory conflict theory is a widely accepted hypothesis on the genesis of motion sickness. There are two types of conflict consisted in this theory, which may provoke motion sickness: one is the conflict between the input signals coming from visual system and vestibular system, as the two examples mentioned in last paragraph, the visual signal indicates the person is stationary but the vestibular system receive a signal that the body's orientation is changing, or vice versa, and both systems simultaneously signal but contradicts with each other; the other is the conflict between expected and actual motion status, like when a sudden turning or acceleration of a car occurs, the expected direction or speed of the human body coming from the body status before turning or acceleration is different from the actual direction or speed status. One of a widely known fact that the driver, even a new driver suffers much lower motion sickness than his passengers may support the sensory conflict theory.

Sensory conflict theory was firstly proposed by Claremont in 1931 that motion sickness occurs whenever there is a discrepancy between the information given to us by one set of sensation and that given by another set of sensation. He stated, "Normally the two sets 'agree' with one another, or rather their occurrence in a given conjunction we are accustomed to we regards as normal. This normality is disturbed on board ship. Our eye here tell us that we are stationary, since we are moving with the room." However, how the output pathways of motion sickness respond to these conflict signals was not defined. The theory has been revised and extended by other researchers since 1931 (Steele, 1968; Reason, 1978). In the early era of this theory, conflict signals were assumed to result from the direct comparison of signals come from different types of sensory, like the conflict between canal and otolith, visual and inertial, vestibular and visual. This definition undertook an important revision by Reason in 1978. He stated that in terms of the actual processing of signals in central nervous system, a direct inter-modality comparison of afferent information is not appropriate because signals from different sense organs have different behavior, and whether they can be said to be conflict or not actually depends on coding, context and previous sensory-motor experience.

He argued that the essential conflict must be between actual and anticipated sensory signals. He rejected the "inter-modality conflict" theories and proposed a "neural mismatch" model based on the "reafference principle" proposed by von Holst in 1954. The basic structural components of neural mismatch model are summarized in figure 1 (Reason, 1978). The "neural store" is the combination of mismatched signals of previous period, voluntary motor control and the actual sensory input from sensory organs. The output of the "neural store" can be viewed as the expected sensory signals. The discrepancy of the expected sensory signals and the actual sensory input is computed in CNS and outputted to generate motion sickness symptoms. An adaptation mechanism can also viewed in this model where a feedback comes from the output of the comparator (mismatch signals) to neural store to adjust the controlled sensory output (the output of the neural store).

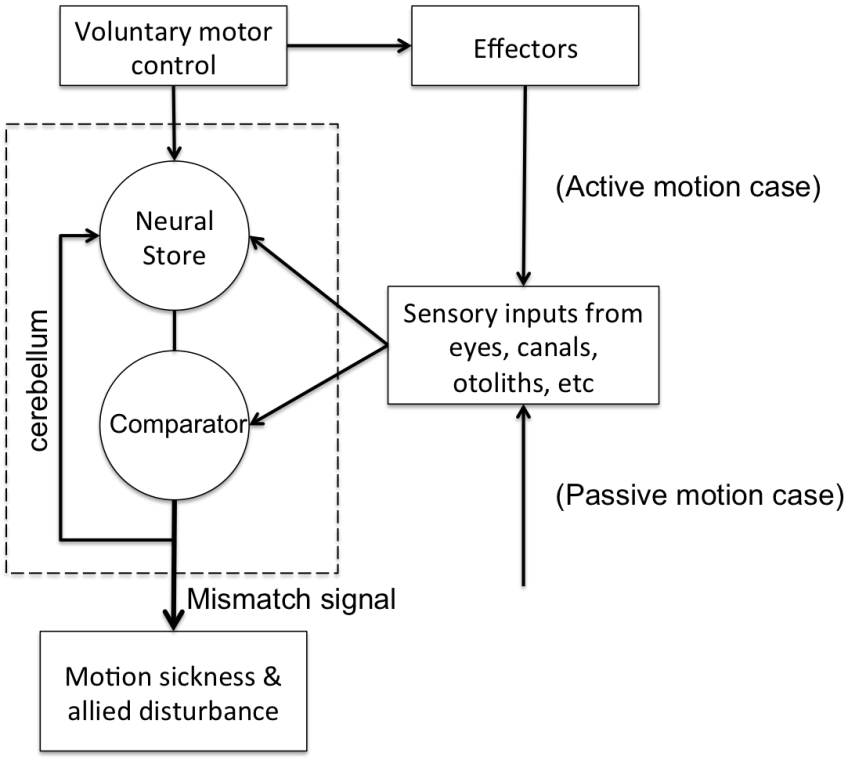


Figure 1: The basic structural components of the neural mismatch model proposed by Reason in 1978 (adopted from Reason, 1978)

Reason's model is only qualitative and the key structural elements such as "neural store" and "comparator" were only intuitively defined. Based on Reason's neural mismatch model, Oman (1982) proposed a mathematical sensory conflict model from the observer theory perspective. The model explicitly defined a major dynamic functional role for sensory conflict signals in movement control and in sensory-motor adaptation. In 1989, Oman proposed a

revised model for dynamic coupling between the putative conflict signals and nausea magnitude estimation. Quantitative models for sensory conflict can be used to predict motion sickness and thus provide an approach to improving the design of visual and motion systems for flight simulators and other virtual environment display systems. Several studies on motion sickness prediction were conducted with modification to Oman's model (Erika, 2002; Paul, 2007).

2.2 Factors related to visually induced motion sickness (VIMS)

The internal causes of motion sickness have been studied for more than 100 years. A lot of bibliographies established the relationship between vestibular system and motion sickness. The vestibular system is the region of the inner ear where the semicircular canals converge. It is responsible for the sensation of balance and motion. It was early found 100 years ago by experiments that animals with bilateral labyrinthectomy could no longer be made sick by artificial ship movement (Kreidl, 1903) and it was also found that people with vestibular dysfunction are immune to motion sickness and patient with partial labyrinthine lesions also have reduced motion sickness susceptibility (Cheung, 1991; Takahashi, 1997). Since motion sickness arises form vestibular system, many proposals on mechanism of motion sickness were based on the role of vestibular system.

2.2.1 Eye motion (EM)

Although it is widely accepted that vestibular-visual conflict produces VIMS, through what media the visual signal transmits to vestibular system, or how this conflict occurs and acts on central nervous system (CNS) to provoke VIMS is still being studied. Since in most circumstances with the occurrence of VIMS eye movements also occur, the role of eye movement in VIMS has been studied for a long time. There are three basic types of eye movements: saccades, smooth pursuit movement and vestibular-ocular movements. Saccades are rapid eye movements that abruptly change the point of fixation, such as the eye movements when you are reading. Smooth pursuit movements are slow tracking eye movements on a moving stimulus to keep it on the fovea. Vestibulo-ocular movements are eye movements compensating for head movements when the observer is trying to track a moving stimulus (Dale, 2001).

It was proposed that eye movement could provoke motion sickness. Experiments showed that blocking afferent signals emanating from stretched extraocular muscle reduced emesis and nausea (Houchin, 1992) and that stimulation of ocular muscle afference produced bradycardia and the risk of cardiac arrest (Money, 1968), providing evidence that eye movement contribute to motion sickness. Among the four types of eye movement introduced in chapter one, optokinetic nystagmus (OKN) has been mostly frequently studied. It was shown that motion sickness could be significantly reduced when the optkinetic nystagmus was suppressed by a stationary eye fixation (Stern, 1990; JI, 2009; Yang, 2011). Ebenholtz (1994) proposed a hypothesis that OKN induce motion sickness. He suggested that it was the extra-ocular muscle traction during OKN that evoke motion sickness by activating the vagus nerve in vestibular system, which is responsible for motion sickness. The reason why OKN could evoke motion sickness can also be explained by sensory conflict theory. OKN is the eye movement induced by visual stimuli in a specific axis. Normal OKN cycle consist of a slow phase and saccadic phase. During the slow phase, human eye involuntarily track the visual target to reduce the retinal slip to keep visual stabilization (Jocelyne, 2009). Retinal slip can be viewed as the conflict between visual and vestibular conflict, which may induce motion sickness. It will be introduced in next part.

2.2.2 Retinal slip (RS)

The hypothesis on the role of eye motion on VIMS has been studied and many experimental results showed that suppression of eye motion can reduce VIMS. However, in these studies, the change of another factor, called retinal slip, is introduced while eye motion is suppressed. Retinal slip is the projected stimuli velocity on retina. There are two kinds of retinal slip occurring during a visual task: one is the foveal retinal slip, defined as the relative velocity of the visual target to fovea during a smooth pursuit task; the other is the peripheral retinal slip, defined as the relative velocity of peripheral part of visual stimulation to peripheral retina. Under the same peripheral stimulus, by adding a stationary eye fixation, eye motion is suppressed while at the same time the peripheral retinal slip is increased. It was suggested that in a large view stimulus, central optkinetic stimulus is responsible for the generation of eye motion and the peripheral optkinetic stimulus is responsible for the generation of circular vection (Brandt, 1973).

Visual target or object of attention is projected on the fovea retina and the other area of vision is projected on the peripheral retina. Hence these two areas of retina slip are functionally different. Peripheral vision is responsible for sense of motion, and can contribute to illusory self-motion, while central vision is responsible for stabilizing visual target, and can also contribute to illusory self-motion when the size of central area is not very small (Brandt, 1973). In past studies, peripheral vision was purely defined or treated as the peripheral part of visual stimuli, however, in many circumstances, there are eye movements, which means the perceived velocities are not just stimuli velocities, but the combination of eye movement velocities and stimuli velocities, so as fovea vision. Therefore, in this thesis, peripheral and foveal retinal slips are studied.

2.2.3 Vection

Visual stimulus, such as large field of moving stimuli, optokinetic stimulus, allow for two perceptual interpretations. The observer may perceive himself as being stationary in a moving surround, or he may experience an illusory of self-motion, which we call vection. Axis or direction of vection depends on stimulus, and intensity of vection varies across subjects and types and duration of stimulus. An extreme circumstance would be the moving surroundings appear to be stable with only self-motion exists. It was shown that vection has correlation with VIMS. Vection has been shown to provoke motion sickness in susceptible subjects (Stern 1985, 1987). It was also shown that vection is a precursor of motion sickness (James, 1999). Based on sensory conflict theory, the reason why vection can provoke motion sickness is it produces the conflict between the actual and anticipated body status by giving an illusory self-motion feeling (anticipated) while the actual body status is stationary. In this study, vection is one of the measured dependent variables.

2.2.4 Others

Stimuli provoking motion sickness can be divided into three categories: one is motion stimulus without visual stimulus; another is visual stimulus without motion stimulus; the third is the combination of the forma two. Most of the circumstances we encounter in daily life that can provoke motion sickness are the third type. For the motion sickness induced by motion stimulus, possible factors like the direction and velocity of the stimulus have been studied, and it is thought that humans reflect the most susceptibility to motion sickness when exposed

to very low frequency vibration (McCauley, 1976). For the visual stimulus, the effect of velocity, types of visual patterns, different axes, color (So, 2007) and time of exposure were studied. It was widely accepted that stimulus velocity has a significant effect on VIMS. It was experimental confirmed that the axes of the scene rotational movements also have significant effect on VIMS. Studies have shown that as the speed of visual scene movement increase, levels of VIMS also increase among the viewers (So *et al.,* 2002) and scene movements in different rotational axes affect levels of VIMS in a similar way (Lo and So, 2001; So and Lo, 1999). Based upon this theory, empirical models have been developed to predict levels of VIMS (e.g., So, 1999; So and Lo, 1999; So *et al.,* 2000; 2001; Yuen *et al.,* 2002). These models have later been developed to biologically inspired computational models (Ji *et al.*, 2004; So, 2004; Ji, 2008).

In 1991, Riccio and Stoffregen proposed that motion sickness in real and virtual environment was caused by prolonged postural instability. It means the continuous disruption on the subject's ability to control his/her body may provoke motion sickness. One phenomenon which can support the strong relationship between motion sickness and postural instability is that most experimental motion sickness was provoked by imposed oscillatory stimuli.

Previous studies showed that postural instability precedes and predicts motion sickness (Stoffregen, 1998) rather than a cause of it.

Since vection and postural instability function more as precursors rather than factors of motion sickness, this study was conducted focusing the role of eye movement on motion sickness, we decided to not to focus on them. Head postures were strictly controlled during all experiments using a chin-rest and vection was measured as one of the dependent variables.

2.3 Research gaps

The first gap concerns the lack of study on the isolated effects of EM and FRS on VIMS. Reviews of literature indicate that reducing EM by eye fixation could reduce VIMS, but during this process, FRSv was also reduced to zero. Therefore, effect of EM suppression was cofounded with suppression of FRS. Foveal retinal slip (FRS) was proposed to have an effect on VIMS (Web, 2003; JI, 2009), but no study was conducted to isolate its effects from EM. One possible reason could be due to the difficulty and challenges in dis-associating EM and FRS. In this study, we successfully isolated EM and FRS using eye-slaved overlaps to

occlude FRS during EM and eye-fixation markers containing drifting strips to introduce FRS while keeping EMv small (see Chapter 4).

The second gap concerns the lack of study on the effects of peripheral retinal slip velocity (PRSv) in the presence of controlled EM. Past studies showed that increasing PRSv could increase VIMS (JI, 2009; Yang 2011), but these results were obtained in the absence of EM. What will be the effect of PRS on VIMS when EM is not suppressed? No study could be found to address this research question.

The third gap concerns the generalization of reducing VIMS by suppressing EM. Past studies investigating the reduction of VIMS by EM suppression have only used purpose-built laboratory type visual stimuli such as moving black-and-white stripes. Whether we can generalize this conclusion to game playing situation is not clear. This is an important gap because in 2005, ISO workshop agreement 3 concluded that VIMS and its reduction among game players is an important research area (IWA3, 2005). In particular, my research will address the following two questions: first, whether EM can be effectively suppressed by an eye fixation marker among game players? Second, if EM can be effectively suppressed, will VIMS be reduced?

Finally, as far as we know, the forth gap concerns the quantification of the relative contributions of EM, PRS, and FRS on levels of VIMS after exposure to visual stimuli. My research will address this gap through regression analyses and survival analyses. In addition, the interacting effects of EM, PRS and FRS on VIMS will be analyzed and organized as potential tools to predict VIMS to be provoked by a particular computer game.

This thesis will present details and results of four experiments and a modeling effort to fill these four research gaps.

2.4 Objectives and thesis outline

The objective of the thesis is to study effects of eye motion (EM), foveal retinal slip (FRS) and peripheral retinal slip (PRS) on visually induced motion sickness (VIMS).

The first chapter presents an introduction to VIMS.

The second chapter presents a literature review on the mechanism of VIMS and factors related to VIMS. After this, research gaps are identified and an overview of the whole thesis is presented.

The third chapter presents the details of experiments include the construction of the visual stimuli, methods to control and isolate EM, PRS, and FRS and apparatuses used in the experiments.

The fourth chapter presents the motivation, design of experiment, procedure, data collection, results analysis, conclusion and discussion on Experiment one. The objective of Experiment one is to study the effects of FRSv while isolating the effects of EMv.

The fifth chapter reports the details and results of Experiment two. The objective of Experiment two is to study the effects of PRS in the presence of controlled levels of EMv and FRSv.

The sixth chapter presents Experiment three and Experiment four. The objectives of Experiment three are to study whether controlling EM during game playing can be effective and if so, whether it can reduce VIMS. EM and VIMS under active game playing situations and passive game watching situations will also be studied and compared. The objective of Experiment four is to study the types of EM during passive game watching situations, and whether the addition of an eye fixation marker can reduce VIMS when viewers are passively watching computer games.

The seventh and eighth chapter presents the details and results of a series of regression and survival analyses. The objective is to study the relative contribution of EM, FRS and PRS to VIMS. A methodology to predict ability of a computer game to provoke VIMS is also presented.

The final chapter is a summary of the thesis and the contributions of the work.

Chapter 3 Introduction to experimentation

3.1 Introduction

The objectives of this thesis are two three-fold: (i) studying the isolated effects of eye movement velocity (EMv), peripheral retinal slip velocity (PRSv) and foveal retinal slip velocity (FRSv) on visually induced motion sickness (VIMS); (ii) modeling the interacting effects of EMv, PRSv and FRSv on VIMS; and (iii) studying the role of EMv on VIMS during game playing. The review of literature in Chapter 2 has indicated that EMv, PRSv and FRSv are potential factors affecting VIMS, however, their individual effects had not been studied in isolation.

The aim of this chapter is to introduce the experiments conducted to achieve the above objectives.

3.2 Overview of experimentation

Four laboratory experiments were conducted. The first experiment examined the effects of EMv and FRSv on VIMS. The second experiment studied the effects of PRSv on VIMS. The third and fourth experiments investigated the effect of eye motion during computer game.

3.3 Equipment

In experiment one and two, a virtual optokinetic drum with vertical black and white strips was set up to provoke VIMS. Different conditions and experiments may have slightly different stimulus in the central part, which will be explained in detail next few chapters. Eye motion in horizontal and vertical direction was recorded by EOG 100C BIOPAC®. In both of the two experiments, subjects were instructed to keep their heads stationary by holding their chins on a chin rest. Stabilizing the head was to prevent vestibulo-ocular movements, which is the combination of eye motion and head motion. To prove that the subjects' head keep stationary, their head motions were recorded by a video recorder and their body vibration was recorded by FASTRAK system. In experiment one, eye tracker VT1 from Eye Tech Digital Systems

Inc. was used to detect subjects' eye position. Real-time eye position data was accessed by a C++ program to draw the position on the screen.

In experiment three and four, a 27 inch LCD displayer was used to display the computer game. Eye tracker was used to record subjects' eye position. Varying from conditions, keyboard and mouse were provided for subjects to control the game or not. Similar as in experiment one and two, subjects were also required to hold their heads still on the chin rest. In the following sections, the 3-screen projection system is introduced.

3.3.1 The 3-screen projection system used in presenting visual stimulus

In experiment one and two, visual stimulus were projected to a virtual optokinetic drum. The framework of the virtual optokinetic drum was made of an 183cm × 460cm curved wide-angle screen, and a visual stimuli was generated in a computer and projected to the curved screen by three projectors to constructed a virtual optokinetic drum with height of 120cm (480 pixels) and radius of around 115cm (Figure 2). For the three projectors (A, B and C in figure 2), projector A was fixed on the left-top of the screen to project the right part of the screen; projector B was fixed on the front-top of the screen to project the central part of the screen; and projector C was fixed on the right-top of the screen to project the left part of the screen. The right part projected by A and the central part projected by C has an overlapping area of 40 pixels, so as the left part and the central part. By standing on the black dot in figure 2, subjects had a 205.9° (1800 pixels) field of view.

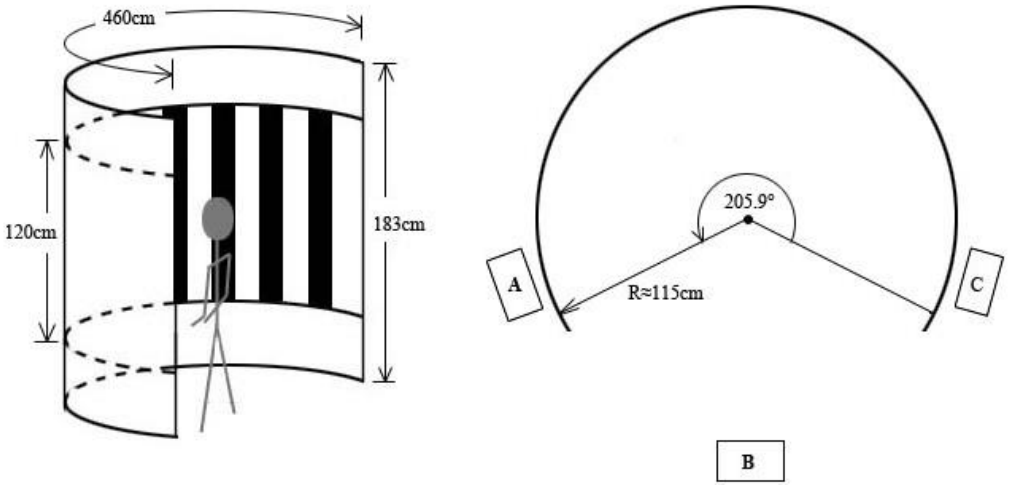


Figure 2: Illustration of the virtual optokinetic drum. The left one is 3D view and the right one is the top view. A, B and C represent the three projectors.

3.3.1.1 Hardware of the 3-screen projector

The computer for generating visual stimuli was equipped with a Intel (R) Core (TM) 2 Duo CPU E6750 (2.66GHz, 3.26 GB of RAM), NVDIA GeForce 8800 GTS 512 for display adapter and Microsoft Windows XP Professional Version 2002 Service Pack 2 for system.

3.3.1.2 Software of the 3-screen projector

A C++ program which applying libraries from OpenGL written in Microsoft Visual Studio 2008 was used to generate visual stimuli. In experiment one, eye tracking software API downloaded from Eye Tech Digital Systems Inc.'s website was used to develop calibration program and real-time-drawing-eye-position program.

3.3.1.3 Generation of the visual stimuli

The C++ program included 2 modules: pre-process images and project images.

Pre-process images included drawing and filtering the frames used to project. The objective of filtering was to extract the effect introduced by the two overlapping areas. The images for projecting were drawn black and white strips with or without a stationary central point. The view angle of one black strip and one white strip summed up to approximately 15° (133 pixels), with 5.72° (83 pixels) for black strip and 9.49° (50 pixels) for white strip. The reason why they hold different view angles is to reduce the possibility of motion sickness provoked by the stationary black and white strips. Before the main experiment, there might be sometimes when subjects stare at the stationary pattern although we asked them to close their eyes until the main test start.

Totally 133 images named from "b001.bmp" to "b133.bmp" were drawn for projecting. Two successive images differed by one-pixel interval. Offset in pixels between two consecutive .bmp file and the parameters of a delay function in the C++ program were calibrated to match the required velocities. Since we were constructing the stimuli slide by slide, we had the full control over the frame rates.

3.3.2 Equipment used in eye movement tracking

3.3.2.1 EOG recordings

Relative eye motion was measured by the EOG 100C developed by BIAPAC®. The EOG100C senses the corneal-retinal potential inherent in the eyeball. As the eyes move in the horizontal and vertical directions, these potentials are added up to generate a voltage variation in the region immediately surrounding the eye sockets.

3.3.2.1.1 Hardware of EOG

The system includes two modes of eye motion recording: one is absolute eye motion using DC mode, the other is relative eye motion using AC mode. Since eye position was not a measurement in both of the two experiments, and the AC mode can provide much more stable output compared to DC mode by extracting the effect of zero-point floating introduced by temperature changing, relative eye motion mode was selected both of the two experiments. The gain of the voltage output was set to 5000 and the output range was ±10V. Frequency response was set to high pass mode (AC: 0.05Hz).

To measure both horizontal and vertical eye motion, two EOG100C modules were set up. Two shielded electrode leads (LEAD110S) were used to connect one EOG100C module and two EL503 electrodes to detect the horizontal eye motion, and another two shielded leads were used to connect the other EOG100C module and another two EL503 electrodes to detect the vertical eye motion. One unshielded electrode lead (LEAD100) was used for ground. The setup for EOG100C modulus to record eye motion is demonstrated in Figure 3.

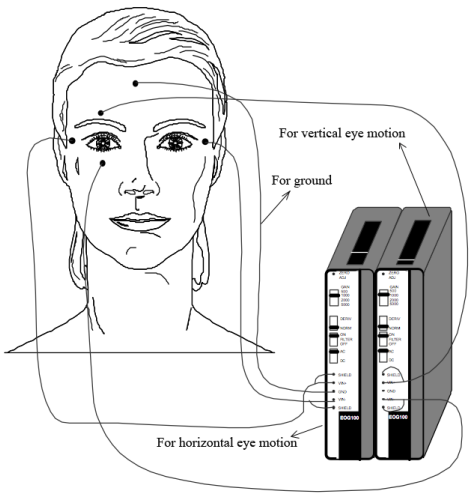


Figure 3: Setup for EOG100C measurement (copied from EOG100C manual)

3.3.2.1.2 Software of EOG

AcqKnowledge 3.7.3 was installed in a host computer to synchronously record the data transmitted from the EOG100C modulus. Two channels of data, horizontal and vertical, were recorded in these two experiments.

3.3.2.1.3 EOG calibrations

Before the main test, calibration test between voltage and degree was carried on. Two dots, left and right of the central point of the screen were projected alternately twelve times for one minute. The distant between the two dots had a view of angle of 15°. The voltage changes when the subject moves his/her eyes from one dot to another dot were recorded and averaged. The mapping constant from voltage to degree was calculated by dividing 15° by the average voltage change from one dot to another dot during the test. The slow phase velocity (SPV) is the speed of smooth eye pursuit during OKN. The SPV for one OKN cycle equals to the slop of the slow phase under the unit of voltage times the mapping constant.

3.3.2.2 Camera-based Eye Tracker

Eye tracker was used in experiment one, experiment three and four.

3.3.2.2.1 Hardware of the camera-based eye tracker

Gaze position was measured using eye tracker VT1 from Eye Tech Digital Systems Inc. The eye tracker was installed with a computer (Figure 4). It was placed below and displayer, with a horizontal distance from subject generally from 50cm to 60cm. The angle of the camera in the middle of eye tracker can be adjusted to match the subject's eye position. There was a connection wire between eye tracker and the computer to transfer data from the eye tracker.

VT1 uses IR lights to illuminate the eyes and provide reference points for the eye tracker. The IR light is produced by LED's at a wavelength of 850 nanometers. This type of IR light occurs naturally in sunlight and in light from incandescent lamps. The total power consumed by the lights is approximately 3 watts. The measured irradiance at the user's eye under normal operating conditions is less than 1 milliwatt per square centimeter. This is well within the safety guidelines given in the book 1996 TLVs and BEIs by the American Conference of Governmental Industrial Hygienists (VT1 hardware installation manual).

Figure 4: Eye tracker, VT1, from Eye Tech Digital System Inc, in the middle there is a camera to capture eye position; at each of the two corners there is an IR transmitter.

3.3.2.2.2 Software of the camera-based eye tracker

Quick Glance 6.5, which can be downloaded from Eye Tech Digital System Inc.'s website, was used to connect the eye tracker and provide a user interface to adjust and calibrate eye tracker as well as obtain the eye position data in terms of pixel on the screen. Basic steps to set up the software are: 1, enter Quick Glance password, which can be found at the eye tracker; 2, enter working distance and camera lens; 3, adjust the angel of the eye tracker to make subject's eyes approximately in the middle of the window; 4, rotate the camera on the eye tracker, to make sure subject's eyes clear in the window. Correct positioning will create one large crosshair and two smaller crosshairs as show in Figure 5.

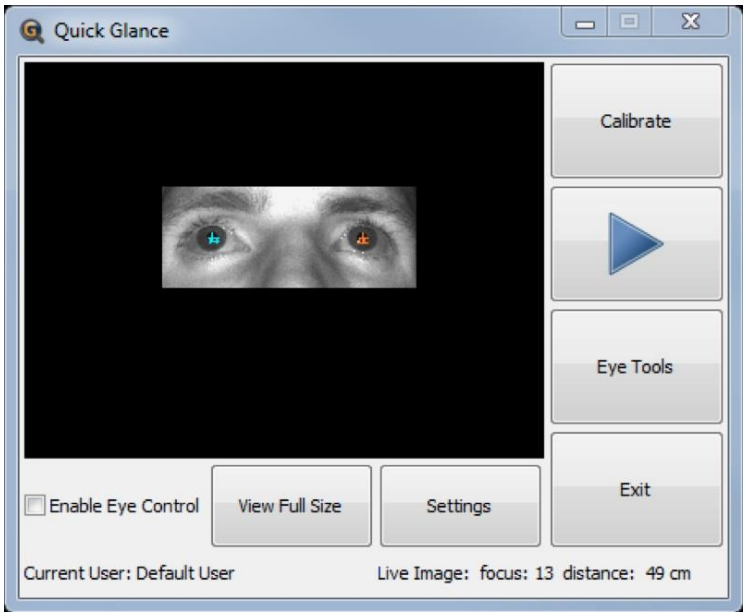


Figure 5: Quick Glance window, cited from manual of Quick Glance downloaded from the company website.

The calibration procedure follows after the “Calibrate” icon is clicked. Subjects were asked to look at the center of each target (Figure 6). It will turn green and then the target will move to the next location. Follow the target as it moves to each location. It will move from left to right, up to bottom.

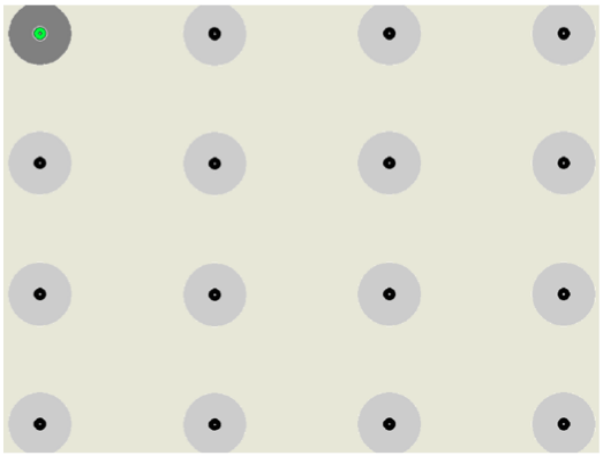


Figure 6: Calibration window presented to subjects

In experiment one, eye tracker was mounted on a wooden platform between the curved screen and the subject (Figure 7). In experiment three and four, it was placed under the 27 inch LCD displayer and facing the subject (Figure 8). Position of the eye tracker was carefully adjusted to make sure it could capture subject’s eye position within the required field of view.

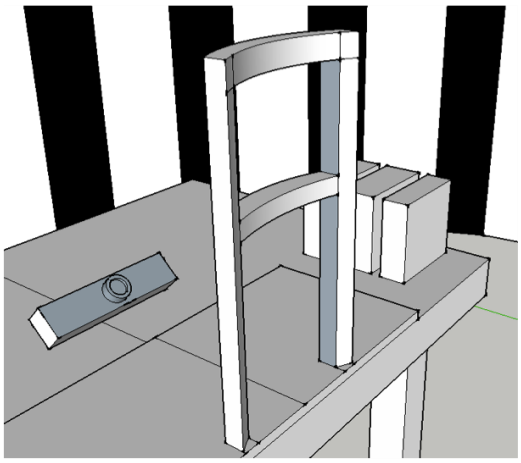


Figure 7: Eye tracker in experiment one

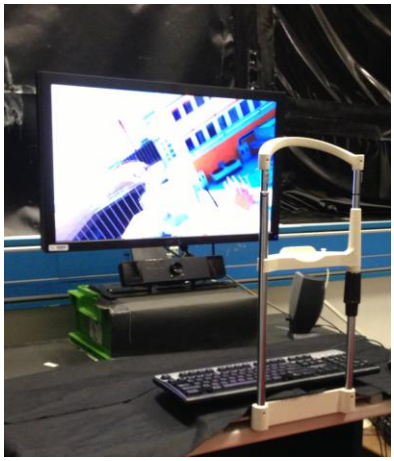


Figure 8: Eye tracker in experiment three and four

3.3.3 Equipment used in body motion tracking

Body/head motion was tracked by FASTRAK system developed by Polhemus. The system uses electromagnetic to determine the position and orientation of a remote object.

3.3.3.1 Hardware of the FASTRAK system

The FASTRAK system consists of a System Electronics Unit, one receiver and one transmitter. The System Electronics Unit contains the hardware and software necessary to generate and sense the magnetic fields, compute position and orientation, and interface with the host computer via RS-232. The transmitter was to produces the electrode-magnetic field and is the reference for the position and orientation measurements of the receivers. It was mounted in a non-conductive (wood) plane located close to the receiver. Dimension plot and real view of the transmitter are demonstrated in Figure 9 and Figure 10.

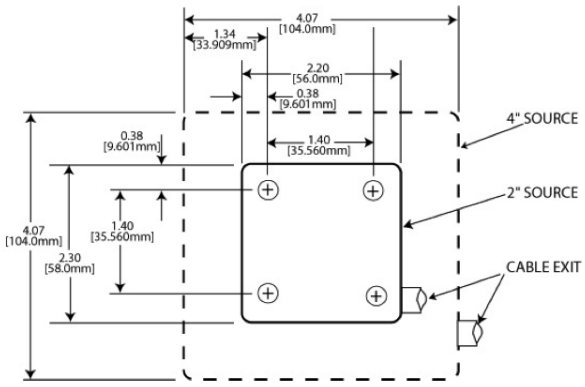


Figure 9: Dimension plot of the transmitter (Copied from FASTRAK manual)

Figure 10: Real view of the transmitter

The receiver was mounted in the subject's body/head to measure the position and orientation relative to the transmitter. Dimension plot and real view of the receiver are demonstrated in Figure 11 and Figure 12.

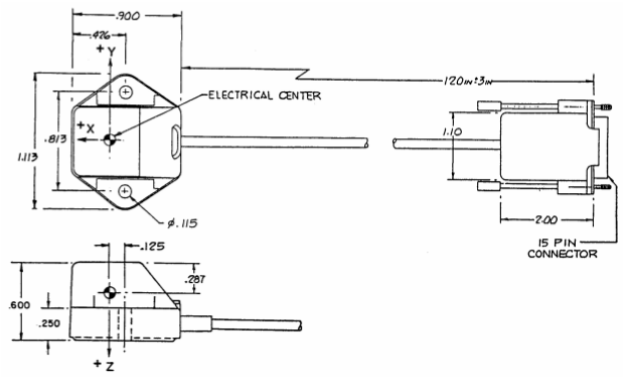


Figure 11: Dimension plot of the receiver (Copied from FASTRAK manual)

Figure 12: Real view of the receiver

The required operating temperature for the FASTRAK system is 10°C to 40°C at a relative humidity of 10% to 95% non-condensing.

The host computer was equipped with Intel (R) Pentium (R) 4, 2.02G Hz, 512M of RAM.

3.3.3.2 Software of the FASTRAK system

A Polhemus GUI was installed in the host machine for the FASTRAK system to record the position and orientation of the receiver. The position and orientation data of the receiver can be recorded one sample at a time by one mouse-click, or recorded continually at a frequency of around 80Hz. There are six degrees in one data sample: X, Y, and Z in Cartesian coordinates for measurement of the receiver's position, Azimuth, Elevation and Roll angles for measurement of receiver's orientation. X, Y and Z were measured in inches or centimeters. All X, Y and Z given in this thesis were measured in centimeters. Azimuth, elevation and roll angles were measured in degrees.

3.3.3.3 Mounting of the FASTRAK sensors

The receiver of the FASTRAK system was mounted on a belt (Figure 13) for spinal adjustment worn on the subject's back to record the body movement. The belt was tight enough to prevent relative motion between the trunk and the belt.

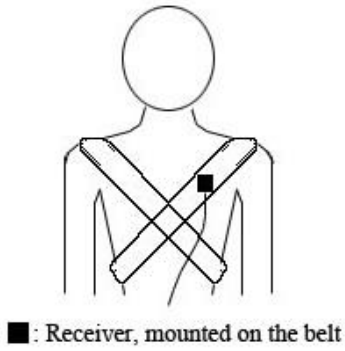


Figure 13: Receiver mounted on the spinal adjustment belt in experiment one

The coordinate system defined by X, Y and Z axes is demonstrated in Figure 14. View the virtual drum as a hollow cylinder, X axis is vertical to the ground surface, represents the up and down motion of the subject's trunk/head; Y is vertical to X and parallel to the tangent plane of the cylinder at the central point of the screen, represents the left and right motion of the trunk/head; Z is vertical to the X-Y plane, represents the fore and back motion of the subject's trunk/head. The error of the measurement of the receiver's position reference to the

transmitter is within 2% (Appendix I). The Azimuth, Elevation and Roll angles represent the orientation changing to the original orientation. The orientation on clicking the "Borsight" button of the software is defined as the original orientation.

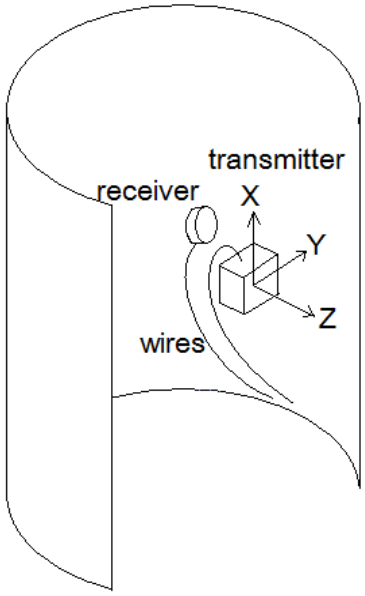


Figure 14: Definition of X, Y and Z axes

3.3.4 Overall setup of the experiment

Equipment used in experiment one was: optokinetic drum, eye tracker, EOG 100C, chin rest, FASTRACK system, cameras and several computers. Coordination of equipment is shown in Figure 15. Equipment used in experiment two was similar as experiment one except that it did not use eye tracker. Equipment used in experiment three and four was: 27-inch LCD displayer, chin rest, keyboard, eye tracker and several cameras and computers (Figure 8).

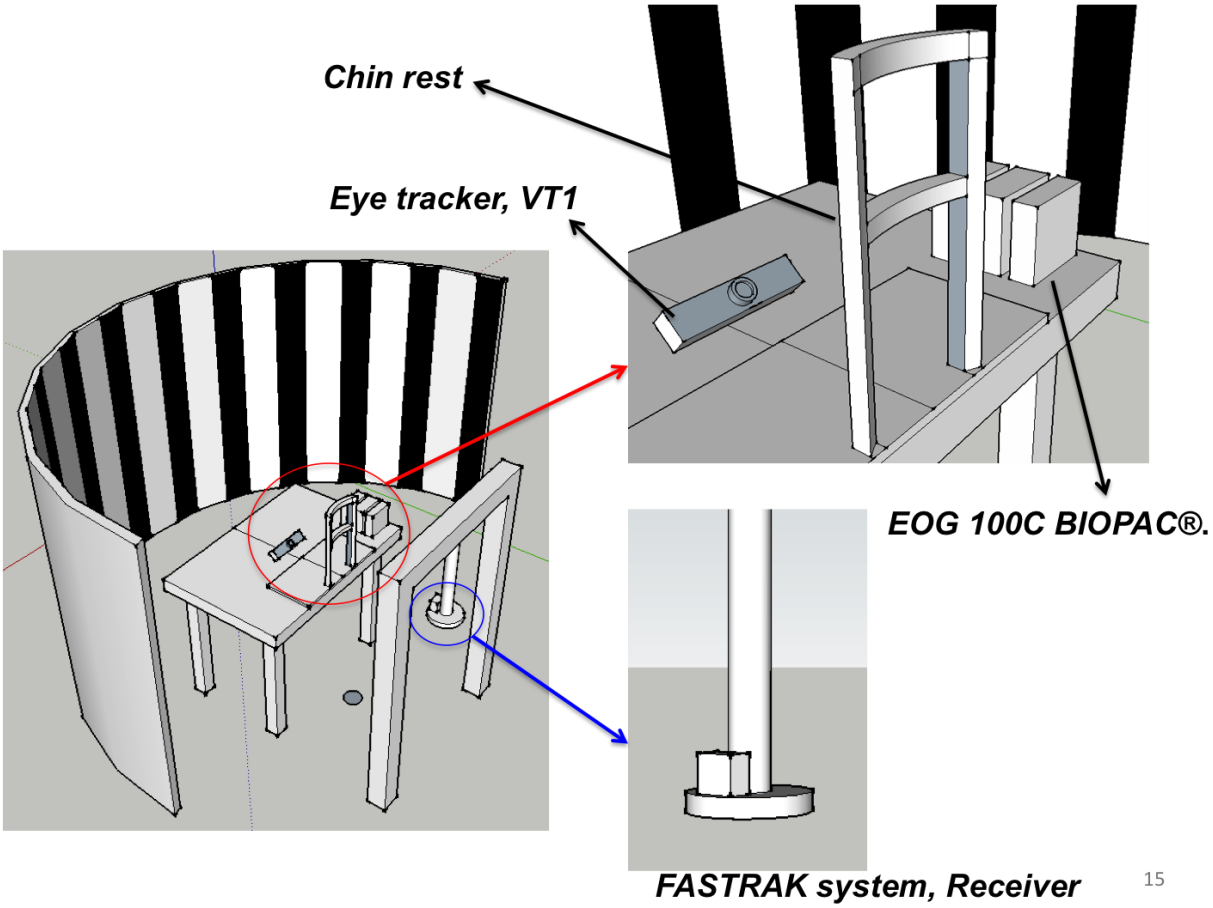


Figure 15: Coordination of equipment in experiment one

3.4 Design of experiment

Since the inter-subject variability in susceptibility to VIMS is large with about 1/3 of the population are susceptible (So *et al.*, 1999), within-subject design was adopted in all four experiments to minimize the influence of inter-subject variability. Susceptibility to VIMS can be adapted (Sugita *et.al.*, 2007; Regan, 1995). In order to minimize the effects of adaptation, each condition were separated by at least 7 days.

3.5 Subjects

The subjects were university students with normal or corrected eye sights. They had been tested to attain at least 20/20 visual acuity. Written consent was obtained and all experiments had been approved by the Human Subject Committee of the Hong Kong University of Science and Technology.

3.6 Data analysis

Both parametric, namely ANOVAs, and non-parametric statistics are used in this thesis. Decision on the type of statistical tests depended on the distribution of the data. Both R and SPSS statistical software had been used. The level of significant was set at 5% level (i.e., $p<0.05$).

Chapter 4 Experiment one: role of eye motion (EM) and foveal retinal slip (FRS) on visually induced motion sickness (VIMS)

4.1 Motivation

Eye motion (EM) has been theoretically proposed and empirically verified to be an important factor associated with the generation of visually induced motion sickness (VIMS) (Ebenholtz *et al.*, 1994; Ji *et al.*, 2009; Stern et al., 1990; Webb and Griffin, 2003; Yang *et al. 2011*). Ebenholtz and his colleagues predicted that abnormal eye muscle traction can provoke VIMS. In previous studies investigating the role of EM in VIMS, eye fixation pointers were used to suppress EM in order to compare conditions with and without EM. In so doing, foveal retinal slip (FRS) was also suppressed. Consequently, when Stern *et al.* (1990) reported that eye fixation reduce motion sickness, it could be the reduction of FRS that had contributed part of the reduction in VIMS.

FRS occurs when projections of a visual target on the retina cannot be completely stabilized by ocular reflex (e.g., optokinetic nystagmus: OKN or vestibular ocular reflex: VOR). In other words, FRS occurs when our eyes fail to track a visual object perfectly. Central vision represents our visual attention and ocular reflex enables our gazes to following moving objects so that we can perceive the objects clearly. When we are exposed to moving scenes, OKN enable our eyes to following the projections of the moving scenes. However, OKN gains are not unity and eyes could not following the visual object perfectly. This causes FRSs. According to the sensory rearrangement theory (Reason, 1978), pro-long exposure to FRS could be a factor that contributes to VIMS. Chen and Stoffregen in 2011 found that motion sickness of passive game players are higher than active players (Chen and Stoffregen, 2011). One possible explanation is that during active game playing, subjects performed more target pursuit EM than in passive game playing. The former may result in lesser FRS. To illustrate the logics, imagine the case when subjects can anticipate where the target is going and the case when subjects are not aware of the future direction of the target, FRS should occur more frequently in the second case.

Ji *et al.* (2009) studied the role of EM in VIMS in terms of changes in foveal and peripheral retinal slip under the absence of vection. Her results were consistent with Stern *et al.* (1990)'s findings that eye fixation could reduce FRS to zero and could significantly reduce VIMS at the same time. Ji and her colleagues also proposed that FRS is more important than PRS when vection is purposely suppressed. In 2011, we found that EM can still increase VIMS when PRS had been controlled (Guo *et al.*, 2011). However, in that study, only PRS was controlled and FRS was cofounded with EM. In 2011, Yang studied effects of voluntary and involuntary EM on VIMS. In his experiment, due to limitation of apparatus, foveal region was not completely blocked, and difference between high and low levels of foveal retinal slip velocity (FRSv) was not large enough to generate a significant effect on VIMS (Yang *et al.,* 2011).

4.2 Challenges and difficulty in isolating EM and FRS

The difficulty of independently manipulating eye motion velocity (EMv) and foveal retinal slip velocity (FRSv) results from the fact that as eyes move, FRSv changes. Consequently, levels of FRSv are not only related to the velocity of visual target, but also the EMv. Secondly, while movements of visual background can trigger optokinetic nystagmus (OKN) – a type of EM, the velocity of the EM (we refer to the velocity of the slow phase of OKN EM) varies with individuals. For examples, the average slow phase velocity is around 40 dps (EMv) when visual target velocity is at 60 dps but we had to empirically measure this if when we controlled the EMv. The third difficulty is how to achieve non-zero foveal retinal slip velocity with simultaneous zero eye motion. We conducted many pilot studies to explore ways to manipulate subjects' EMvs in Experiment one so that we were able to obtain the pre-determined ranges of average EMv. Particular solutions developed to tackle the above stated difficulties will be explained in the following sub-sections.

4.3 Objective and hypothesis

The objective of our study was to isolate the effects of foveal retinal slip velocity (FRSv) and the effects of eye motion velocity (EMv) under controlled peripheral retinal slip velocity (PRSv). We hypothesized that when EMs are the same, conditions with higher FRSv would produce higher VIMS than condition with zero FRSv (referred to as the FRS hypothesis). When FRSv are the same, either zero or non-zero, conditions with higher EMv would

produce higher levels of VIMS than conditions with zero EMv (referred to as the EM hypothesis).

4.4 Materials and apparatus

A virtual optokinetic drum with vertical black and white stripes was used to present the visual stimuli. This drum was used in previous studies (Ji *et al.*, 2009; Guo *et al.,* 2011; and Yang *et al.*, 2011). Technology specification of the drum can be found in Chapter 3. EMs along horizontal and vertical directions were recorded both by EOG and a camera-based eye tracker. The former was used because previous studies used EOG to measure the EM patterns and we would like to be consistent (Ji *et al.*, 2009; Guo *et al.,* 2011; and Yang *et al.*, 2011). The latter was used to facilitate an eye-slaved elliptical marker. This elliptical marker would block the subjects' central vision so as to reduce FRSv to zero. Participants were instructed to keep their heads stationary using a chin rest. To verify that the subjects did not move their heads, head motion was recorded by a video recorder and body vibration was recorded by the FASTRAK system from Polhemus (see Chapter 3). We did try to put a Polhemus position tracker on the subjects' heads but it interfered with the EOG electrodes. Consequently, we put the Polhemus tracker on the body and used a video recorder to record head movements. Through out the experiment, the heads of the participants were observed to remain stable.

Detail specification of apparatus and their position can be found in Chapter 3.

4.5 Design of experiment

Eye motion velocity (EMv) was defined as the slow phase velocity of the measured optokinetic nystagmus (OKN). There are two reasons for using the slow phase velocity as the EMv rather than the saccadic phase velocity or the average of the two: first, longer than 90% of the total time in one OKN cycle is slow phase (Figure 16); second, during saccadic phase, eye motion velocity is too high for one to clearly see the stimuli, and its value dose not vary from stimuli velocities. The lower part of Figure 16 illustrates signals of eye motion velocity (EMv), foveal retinal slip velocity (FRSv) and peripheral retinal slip velocity (PRSv).

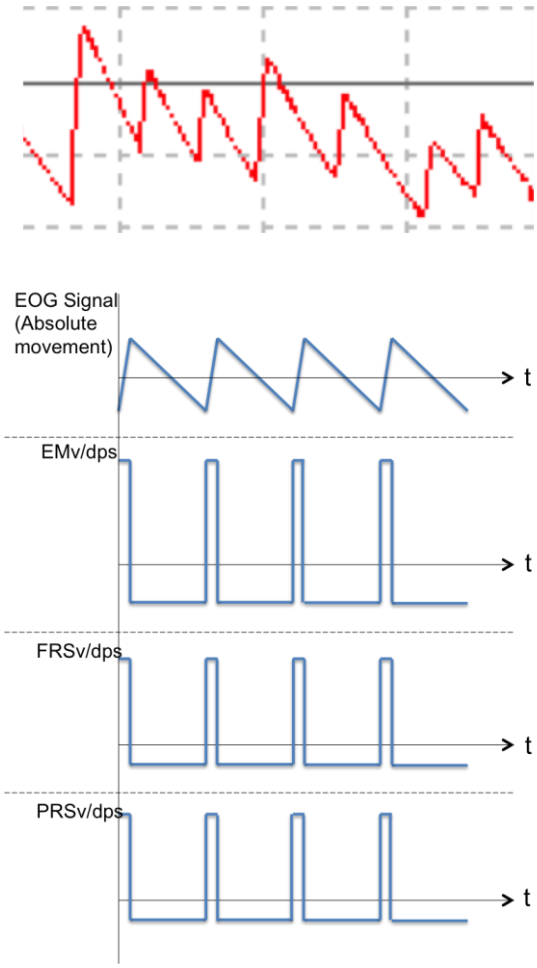


Figure 16: A typical EOG OKN signal (1st plot), steeper part is saccadic phase of OKN, and gentle part is slow phase of OKN. The horizontal axis is time consumed, and the vertical axis is voltage. Other plots are illustration on EMv, FRSv and PRSv.

Foveal retinal slip velocity (FRSv) was defined as the velocity of the projection of the visual target on the foveal region of the retina during the slow phase of OKN. Peripheral retinal slip velocity (PRSv) was defined as the velocity of the visual projection on the peripheral part of the retina during the slow phase of OKN.

The experiment was a 2×2 full factorial within-subject design. Independent variables were EM (+, with EM (about 35°/s to 40°/s); -, without EM (zero or 7°/s to 10°/s) and FRSv (+, FRSv was around 15°/s; -, FRSv was 0°/s). Details about every condition are illustrated in Table 2: condition A (EM: +, FRSv: -), condition B (EM: +, FRSv: +), condition C (EM: -, FRSv: -), condition D (EM: -, FRSv: -). The four conditions are illustrated in Figure 17.

Table 2: specification of experimental conditions. “Bv” is background stimuli velocity; “Cv” is central velocity or the visual target velocity

Con.	EMv °/s	FRSv °/s	Bv °/s	Cv °/s	PRSv °/s
A	+: 35~40	-: 0	50	40	15
B	+: 35~40	+: 10~15	50	NA	15
C	-: 0	-: 0	15	0	15
D	-: 7~10	+: 15~18	25	25	15

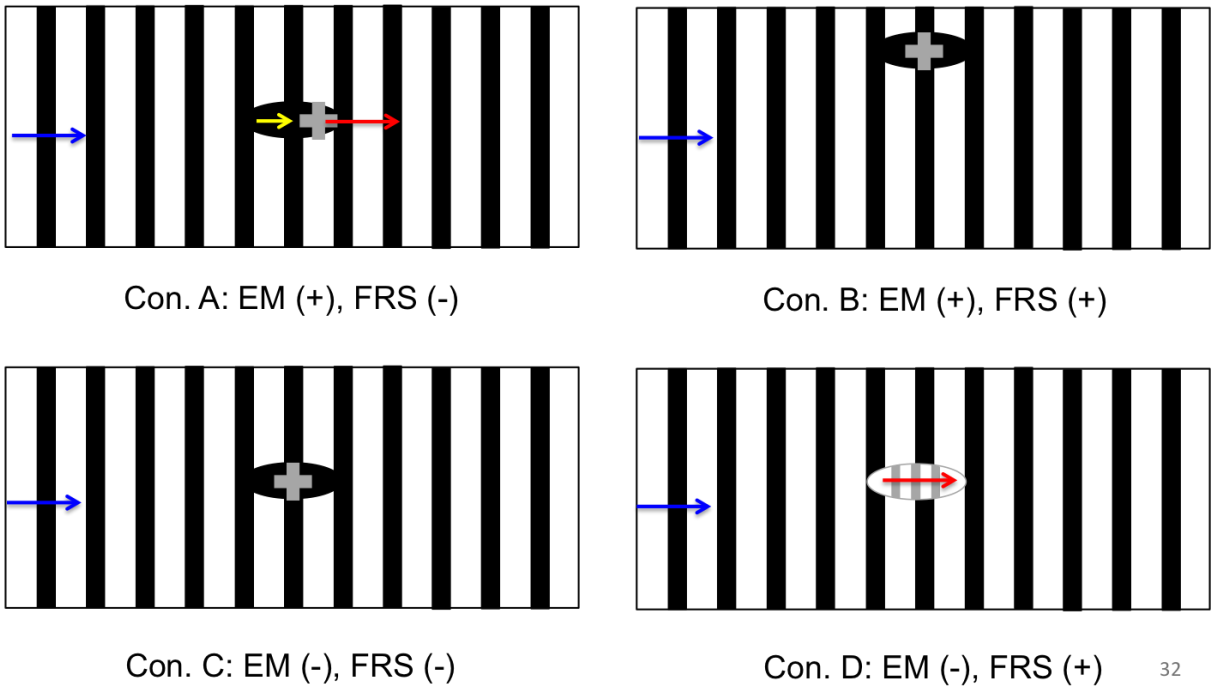


Figure 17: illustration of the four conditions and levels of EM and FRS. Arrows identify direction of velocities. If there is no arrow, velocity equals to 0.

In this experiment, the independent variables were EMv and FRSv and the control variable was the PRSv. Both EMv and FRSv were manipulated by careful control of the velocities of the central part of visual stimuli (Cv) and the background part of the visual stimuli (Bv). These values of these velocities were based upon results of many pilot tests. In condition A, the subjects’ lines of sight were guided by a gray moving cross to produce similar patterns of EMs as in condition B. In the latter condition (i.e., condition B), the foveal region of subjects’ lines of sight was blocked by a black eye-slaved ellipse to facilitate zero FRSv. In condition C, EM was suppressed by a stationary eye fixation marker (a gray cross on a dark ellipse of the same size as in conditions A and B). In condition D, EM was suppressed by a specially designed eye fixation area. Subjects were instructed to keep their eyes at the center of this area, this reduced the EMv to about 7°/s to 10°/s. Inside the eye fixation area (an ellipse with the same size of the eye-slaved ellipse used in Conditions A and B), drifting gray and white

stripes at 25°/s were displayed resulting a FRSv of about 15°/s to 18°/s. In Condition D, the EMv was much about 40% reduction of those in Conditions A and B but FRSv remained as fast as, or even faster than, that in Condition B (about 15°/s). For details of the EMv, FRSv and PRSv in the four conditions, please refer to Table 2.

The vertical position of the eye-fixation cross in Condition A was always in the middle of screen while the horizontal position oscillated from 17.1 degrees to the left of the center of the screen to 17.1 degrees to the right of the center of the screen. This length was decided based on the average amplitude of an OKN cycle during the pilot studies. The size of the ellipse in condition A was 9.1 degrees (horizontal) by 6.8 degrees (vertical). This size was choice so that it ensured that even with the latency of the eye-slave system, the ellipse was able to cover the foveal visual region completely to facilitate zero FRSv. Sizes of ellipses in other conditions were designed to be the same as condition A.

Twelve subjects, 6 males and 6 females, with ages from 21 to 24 participated the experiment. All of them were students at the Hong Kong University of Science and Technology. They were tested to have normal or corrected-to-normal visual acuity. Subjects' written consents were obtained and they received a compensation of HKD50 (about USD6) per hour for their time. The experiment was approved by the Human and Ethics Committee at the Hong Kong University of Science and Technology. In case a subject did not feel well on the day of experiment, he or she was required to have a rest and come back on another day.

In this experiment, the dependent variables were levels of VIMS and vection. Levels of VIMS were measured using a 7-point nausea ratings (Golding and Kerguelen, 1992) as well as nausea ratio scale data with a free modulus magnitude estimation method (McGee, 1998). Pre- and post-exposure Simulator Sickness Questionnaire data were collected (Kennedy *et al.*, 1993; Ji *et al.*, 2009; Kennedy *et al.*, 2010) and rated vection data were also taken (Webb and Griffin, 2003). As described in Chapter 3, subjects' body movements were recorded by the Polhemus FASTRAK system.

4.5.1 Procedure

Before the experiment, subjects were asked to read the instructions for the experiment and sign the consent form. A line length estimation test was conducted to train subjects' ability to give ratio scale ratings. During the test, subjects estimated 20 lines segments with different

lengths from 1cm to 20cm using the free modulus magnitude estimation method. All subjects passed the line length estimation test before main experiment. The susceptibility to motion sickness was measured using a motion sickness susceptibility survey questionnaire and an MSSQ-short questionnaire (Golding, 2006). After becoming familiar with the literal meanings of various VIMS symptoms, subjects completed a pre-exposure Simulation Sickness Questionnaire (pre-SSQ). In order to calculate the EOG mapping constant between voltage and degree, subjects needed to perform an EOG calibration with controlled horizontal EMs of 15 degrees amplitude. A Polhemus FASTRAK position sensor was then mounted on the back of the subjects through a spinal adjustment belt. After that, the subjects were given a 5 - minute break before the main test. After the break, the subjects were exposed to the main task for 30 minutes. During the 30 minutes, their Ems and body positions were continuously measured. In condition A, the subjects were instructed to follow a gray cross; in condition B, subjects were instructed to look straight ahead. In condition C, subjects were instructed to fixate their eyes on the cross. Lastly, in condition D, subjects were instructed to look at the drifting stripes inside the center fixation eclipse.

During the 30-minute exposure, subjects were asked to report subjective nausea levels and vection ratings every 2 minutes. At the end of the exposure, subjects were asked to complete a post- exposure Simulation Sickness Questionnaire (post-SSQ).

4.6 Results

4.6.1 Processing of dependent variables and EOG data

I. Nausea ratio scale data using free modulus estimation

Immediately before the 30-minute exposure of the condition, subject was asked to use a positive number to represent their feeling of normal state of zero discomfort at that moment. During the exposure, every time when the experimenter asked the subject to report the new score, she also reminded the subject his/her ratio scale data reported two minutes ago. The more the subject felt discomfort towards higher nausea, the higher score he/she reported. For example, if the subject felt ‘twice amount’ of discomfort towards nausea as compared to two minutes ago, he/she would double the previous score. On the other hand, if relieved by half, he/she would report half of the previous score.

As the rating was taken every two minutes, there were totally 16 data points of nausea ratio scale data. Because subjects were free to chose different seed number to represent their normal state of zero discomfort, raw data were normalized to facilitate comparisons. The k^{th} (k=1, 2, 3…16) raw data of subject i in condition j was normalized in the following equation:

Normalized ratio scale $data_{ijk}$ = antilog (log (raw ratio scale $data_{ijk}$) - $offset_{ijk}$).

$Offset_{ij}$ is the difference between the average logarithmic raw ratio scale data of subject i in condition j and the average logarithmic raw data of subject i of all 4 conditions.

II. The 7-point nausea rating

In addition to the ratio scale nausea rating, subjects also needed to report their rated nausea level using a 7-point Likert nausea rating. The anchoring description of the ratings is listed in Table 3 (Golding and Kerguelen, 1992). At every interval of 2 minutes, the experimenter would remind the subject the rating he/she gave 2 minutes ago with the descriptions and asked whether he/she would change or give the same rating. For example, at 16^{th} minute, the experimenter said: "your previous rating is E, mild to moderate nausea. D is mild nausea; F is moderate nausea but can continue. What is your current rating? ". The reason why we use 'A' to 'G' instead of 1 to 7 for the rating was that we did not want the subjects to confuse this rating with the vection ratings which was from 0 to 100. Subjects had been educated about the Likert and progressive nature of the 7-point nausea rating and they knew that it was an interval scale (i.e., Symptom in 'C' is more serious than 'B' and symptoms in 'B' is more serious than 'A' and so on). Providing the subject with the next higher and lower levels was based on the fact that in most circumstances the subject will choose these two or stay the same as previous one. It did not mean that he/she must choose them. If the subject felt his/her ratings were not within them, the experimenter would describe other ratings for him/her. The ratings A ~ G were assigned numbers 1 ~ 7 in statistical analysis.

Table 3: Definition of 7-point nausea rating (Adapted from Golding and Kerguelen, 1992)

Rating	Definition
A	No symptoms
B	Any unpleasant symptoms, however slight
C	Mild unpleasant symptoms, e.g. stomach awareness, sweating but no nausea
D	Mild nausea
E	Mild to moderate nausea
F	Moderate nausea but can continue
G	Moderate nausea, want to stop

III. Vection

Vection rating measured the feeling of self-motion. The description of vection feelings used in experiment is listed in Table 4. When analyzed, numbers from 0 to 100 were used instead of percentage.

Table 4: Descriptions of vection ratings

You report	Perception of motion (vection)
0	You feel like you are stationary and it is the image which appears to be moving only.
1-49%	You feel like you are moving a bit, but the image is moving more.
50%	You feel like you are moving at the same speed as the image.
51-99%	You feel like you are moving a lot and the image is moving a bit.
100%	You feel like you are moving and the image appears stationary.

IV. Simulator sickness questionnaire (SSQ) scores

Subjects were required to fill in SSQ table before and after experiment. SSQ is composed of severity ratings of 23 symptoms. Each symptom has 4 levels: none, slight, moderate and severe, which are counted as 0, 1, 2, 3 in calculation of SSQ scores. SSQ total score represents the general rating of motion sickness. There are three sub scores representing three categories of motion sickness: nausea, oculomotor and disorientation. Weightings on the same symptom vary from types of SSQ scores. The detailed calculation formulas can be found in appendix.

V. Eye motion data

The calculation of eye motion velocity (slow phase velocity of OKN, SPV) is described in detail in the appendix.

Since both the eye motion velocity (EMv) and foveal retinal slip velocity (FRSv) were the independent variables whose values had been carefully controlled through complicated manipulation (see Section 4.5), their values in the four conditions needed to be verified. The average eye motion velocity in conditions A and B were 28.3°/s and 32.0°/s respectively, with no significant difference ($p>0.05$: Wilcoxon signed rank test). The lack of significant difference is important as we would like them to be similar in our design of experiment. Average peripheral retinal slip velocities (PRSv) in conditions A and B were 21.7°/s and 18.0°/s, respectively, with no significant difference by Wilcoxon signed rank test. FRSv in condition A was reduced to zero by eye slaved ellipse panel and in condition B FRSv was

18.0°/s. EMs in condition D was verified to be significantly suppressed compared to conditions A and B in terms of SPV. The average SPV in condition D was 8.1°/s (i.e., EMv), which was significantly lower than those in conditions A and B ($p<0.02$, Wilcoxon). PRSv in all four conditions were not significantly different from each other. This verifies that the PRSv was successfully controlled to be similar across all conditions. The actual measured parameters for the four conditions are listed in Table 5, which are similar to the designed values listed in Table 2.

Table 5: Actual measured parameters for the 4 conditions, definition of Bv and Cv is stated in the caption of Table 2.

Con.	EMv °/s	FRSv °/s	Bv °/s	Cv °/s	PRSv °/s
A	+: 28.3	-: 0	50	40	21.7
B	+: 32.0	+: 18.0	50	--	18.0
C	-: 0	-: 0	15	0	15
D	-: 8.1	+: 16.9	25	25	16.9

VI. Body movement data

The average standard deviation of the body movement of 12 subjects in the three axes during the 30-minute exposure was calculated to analyze the amount of body movements. The SDs range from 0.3983 cm to 0.6123 cm, which indicated that all subjects were able to keep the bodies still during the 30 minutes of exposure to the visual stimuli. There was no significant difference among the 4 conditions on the same axis.

4.6.2 Statistical analysis

I. Correlation analysis among nausea ratio scale data, 7-point nausea rating, vection and SSQ total score (SSQT)

The average data across the 30 minutes for each subject in each condition were calculated and used in the correlation analyses. The average 7-point nausea rating significantly correlated with SSQ total score and nausea ratio scale data in all 4 conditions. SSQ total score did not show significant correlation with nausea ratio scale data in most conditions. This may be due to the fact that SSQ scores were obtained after the 30-minute exposure while the ratio scale nausea was the average across the 30 minutes. Vection rating did not show significant correlation with other measurements in most conditions.

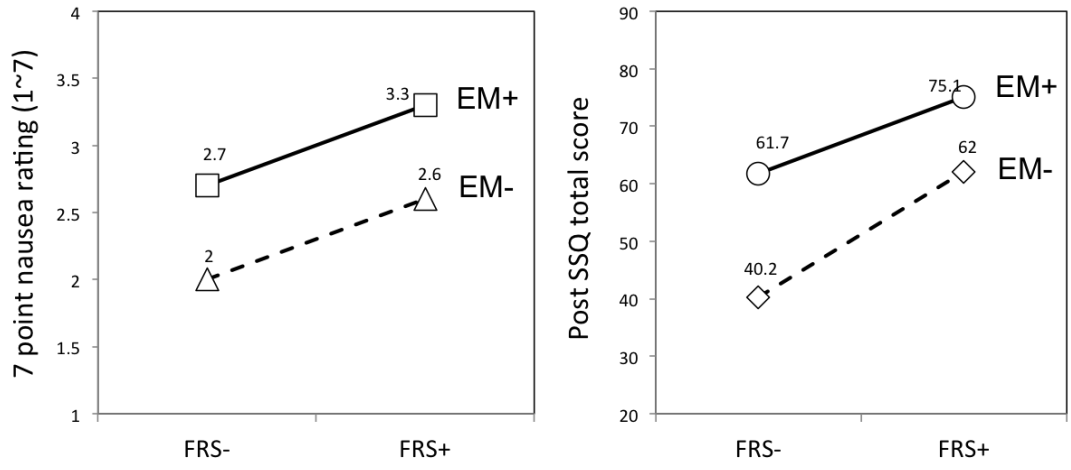
Table 6: Correlation analysis among different measurements

Pairs	Index	Con A	Con B	Con C	Con D
7-point vs. SSQT	*Pearson Corr.*	0.636	0.692	0.773	0.701
	p-value	< 0.05	< 0.05	< 0.01	< 0.05
7-point vs. vection		0.418	0.742	0.545	0.656
		> 0.05	< 0.01	> 0.05	< 0.05
7-point vs. ratio		0.699	0.774	0.592	0.653
		< 0.05	< 0.01	< 0.05	< 0.05
SSQT vs. vection		0.265	0.251	0.269	0.345
		> 0.05	> 0.05	> 0.05	> 0.05
SSQT vs. ratio		0.368	0.519	0.696	0.553
		> 0.05	> 0.05	< 0.05	> 0.05
ratio vs. vection		0.075	0.691	0.018	0.227
		> 0.05	< 0.05	> 0.05	> 0.05

II. Main effect analysis

When EMv was around 35 dps, by Wilcoxon signed rank test, the average 7-point nausea rating (left part of Figure 18) when FRSv was 15 dps (condition B: 3.3) was significantly higher than that when FRSv was 0 (condition A: 2.7) (Z= -2.983 and p< 0.005). The same result (right part of Figure 18) was also found in SSQ total score (Z = -1.968, p < 0.05).

When FRSv was around 15 dps, 7-point nausea rating was significantly higher in condition with EMs (condition B: 3.3) than in condition where EM was suppressed (condition D: 2.6), with Z value of -2.625 and p value of 0.009.



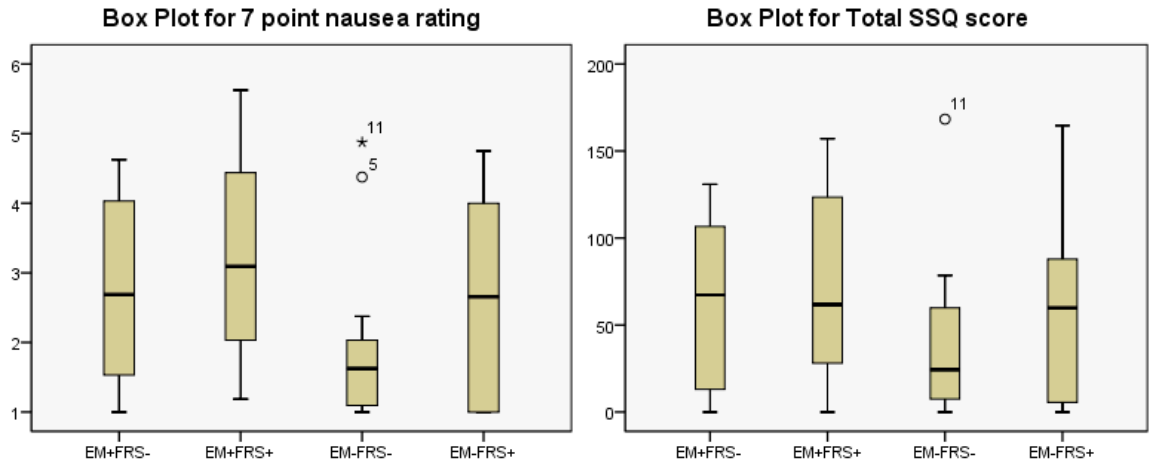
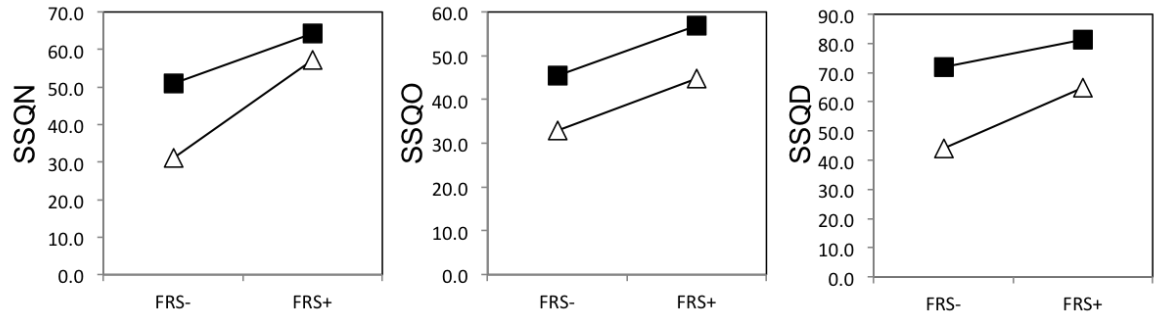


Figure 18: Main effect plots and Box plots of 7-point nausea rating and SSQ total score.

Except for 7-point nausea rating and post SSQ total score, for other measurements (Figure 19), there were no significant difference between either condition A and B, or condition B and D. But the mean values showed the same trend as that of 7-point nausea rating and post SSQ total score. Interaction between EM and FRS was not significant ($p > 0.1$). Nausea ratio scale showed a slightly reverse effect of foveal retinal slip during eye motion existed (EM+FRS+, EM+FRS-), although not significant, and a significant interaction between the two independent factors. Look into the nausea ratio scale ratings in condition "EM+FRS+" and "EM+FRS-", which were inconsistent with other measurements. We found that there are actually 8 subjects out of 12 showed the same trend as other measurements, that they had higher nausea ratio scale ratings in condition "EM+FRS+" than "EM+FRS-". For the remaining 4 subjects, their ratings in condition "EM+FRS-" were so high that they reversed the order of mean values of the two conditions. Likewise, we also found that in condition "EM+FRS+" and "EM-FRS+", 8 subjects out 12 had higher nausea ratio scale ratings in "EM+FRS+" than "EM-FRS+". For these reasons, we treat the inconsistency in nausea ratio scale ratings as some unknown random noise.



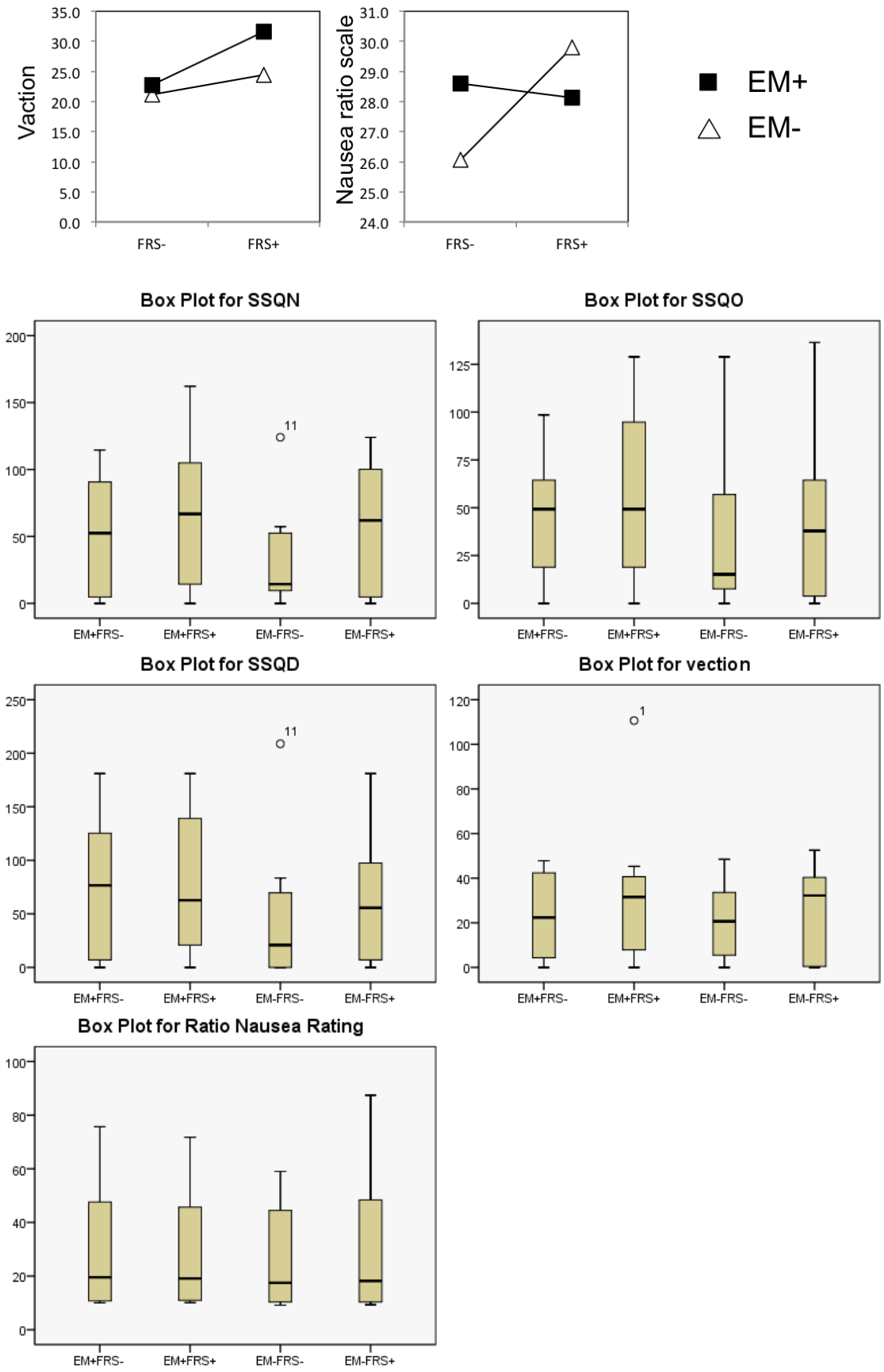


Figure 19: Main effect plots of SSQN, SSQO, SSQD, vection and nausea ratio scale data

III. Time course of 7-point nausea rating

Average 7-point nausea rating of 12 subjects in every minute for each condition are plotted in Figure 20. Inspection of the figure show that the time course effect is obvious and the effects of EM and FRS to VIMS is also obvious.

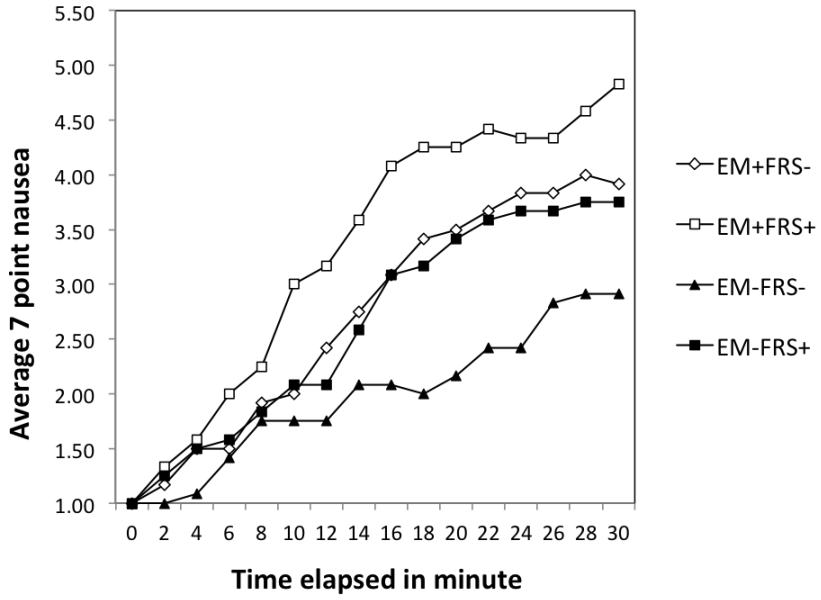


Figure 20: average 7-point nausea rating of all subjects in every minute for each condition

The time taken for each subject to first report mild nausea is shown in Table 7. Some subjects in some conditions did not feel any nausea at all in which case the time is recorded as >30. Four subjects did not feel any nausea in both condition “EM+FRS-” and “EM+FRS+”. For the remaining 8 subjects, 7 of them took shorter time to reach mild nausea in condition “EM+FRS+” than “EM+FRS-”, and the last subject took equal time in the both conditions. In other words, there is a trend that, in the presence of EM, FRS will shorten the time for subjects to reach mild nausea. The same difference is also found between “EM-FRS+” and “EM+FRS+”, where subjects in “EM+FRS+” also took shorter time to first report mild nausea as compared to those exposed to the “EM-FRS+” condition. In other words, in the presence of FRS, EM significantly shortens the time for subjects to reach mild nausea. In summary, results of “exposure time to first report mild nausea” are consistent with other measurements of VIMS.

Table 7: Time for each subject to first report mild nausea under the four conditions

Sub. #	EM+FRS-	EM+FRS+	EM-FRS-	EM-FRS+
1	12	10	26	10
2	>30	>30	>30	>30
3	18	10	>30	12
4	16	14	>30	16
5	14	10	12	12
6	>30	>30	>30	>30
7	>30	>30	>30	>30
8	>30	14	>30	>30
9	>30	22	>30	>30
10	>30	>30	>30	>30
11	12	6	8	16
12	14	14	>30	14

4.7 Conclusion and discussion

Both 7-point nausea ratings and post SSQ total scores indicated that under the similar eye motion (EM) conditions as defined in terms of similar slow phase velocity (SPV) and similar EM amplitudes, reducing the foveal retinal slip velocity (FRSv) to zero by blocking the central vision can significantly reduce levels of VIMS ($p<0.05$). These results support the FRS hypothesis. When EM were suppressed, increasing the FRSv from zero to about 18 degrees per second can increase the post-exposure SSQ total scores from 40.2 to 62 and the difference is marginally significant ($p<0.1$, Wilcoxon tests). Under the same foveal retinal slip velocity (FRSv), reducing SPV and amplitude of EM can significantly reduce rated nausea. This supports the EM hypothesis. From analysis on "Time to mild nausea", we found it will take longer time to reach mild nausea if EM is suppressed or FRSv is reduced. This supports both the FRS and EM hypotheses.

We acknowledge that foveal retina is sensitive to light and colors but not movement of light projections (i.e., projections of visual motion), we are surprised to learn of significant relationship between FRS and VIMS. One possible explanation for the surprising results could be the co-founding between the voluntary nature of eye movements (involuntary and voluntary) and FRS in this study. Involuntary eye motion had been proposed to produce higher VIMS than voluntary eye motion (Ebenholtz *et al.*, 1994; Yang *et al.*, 2011). Another possible explanation for the role of FRS could be its role related to the stabilization of visual target on the retina, which helps stabilize posture in an unstable environment. Past studies

showed that stationary eye fixation helps to stabilize body posture. From the point of sensory conflict theory, blocking the central vision by eye-slaved ellipse reduces visual indication of motion, and therefore reduces conflict with vestibular inputs. Effects of EM on VIMS are further verified in this experiment. In past studies, eye fixation reduces EM and FRS at the same time, and this significantly reduces VIMS. Experiment one's results indicate that after removing effect of FRS, EM still has significant effect on VIMS ($p<0.05$). To conclude, Experiment one filled the gap of studying the effects of eye motion (EM) and effects of foveal retinal slip (FRS) on VIMS under the same peripheral retinal slip (PRS) and in isolation. The next chapter will introduce experiment two which studies peripheral retinal slip.

Chapter 5 Experiment Two: Effects of peripheral retinal slip (PRS) on visually induced motion sickness (VIMS) in the presence of eye motion (EM) and controlled levels of foveal retinal slip (FRS)

5.1 Motivation

In Experiment one, effects of EM and FRS were studied with controlled levels of PRS. Results supported both the EM hypothesis and the FRS hypothesis. In other words, higher levels of VIMS were provoked with increasing EMv or FRSv. According to the two vision system theory (Brandt, 1973), peripheral vision is more sensitive to visual motion and if FRS had a significant influence on VIMS, PRS should have a larger effect. Consequently, studying the effects of PRS on VIMS should be fruitful.

In the past, PRSv had only been studied in the absence of EM (i.e., both EMv and FRSv were zero). Results indicated that higher levels of VIMS will be provoked with increasing PRSv in the absence of EM (Ji, 2009; Yang, 2011). While this was consistent with the two vision systems theory, isolated effects of PRSv on VIMS had not been studied in the presence of EM and FRS. In Experiment one. Hence, in this Experiment two, we will investigate the effects of PRSv on VIMS in the presence of controlled (non-zero) levels of EM and FRS.

5.2 Objective and hypothesis

The objective of experiment two was to study the isolated effect of PRSv on VIMS during EM and FRS. We hypothesized that increasing PRSv during the same EMv could increase VIMS. We refer this as PRS hypothesis. As explained in the previous paragraph, this study was new and had not been reported before.

While the isolated effects of PRSv on VIMS in the presence of EM and FRV had not been reported, the following section presents a quantitative analysis of past studies to support the

hypothesis. During the author's MPhil study (Guo, 2011), a mean rated nausea of 4.01 (mild nausea) was measured in the presence of 40 dps EMv, 20 dps FRSv and 20 dps PRSv. When EMv was reduced to 0 dps by an eye fixation pointer, the mean rated nausea was significantly reduced to 3.08. The reduction of EMv by eye fixation was associated with simultaneous reduction of FRSv (from 20 dps to 0 dps) and simultaneous increases in PRSv (from 20 dps to 40 dps). From the results of Experiment one reported in Chapter 4, other things being equal, reducing the FRSv from around 20 dps to 0 dps resulted in a mean reduction of rated nausea of 0.59. Also, reducing EMv from around 35 dps to 0 dps resulted in a mean reduction of rated nausea by 0.69. If we assume that effects of EMv, FRSv and PRSv had no interaction among each other, combining the results of my Experiment one with the MPhil result, the effects of increasing PRSv from 20 dps to 40 dps could be hypothetically estimated to be 0.35 [0.35 = 3.08 – (4.01 – 0.59 – 0.69)]. The calculation process is illustrated in Figure 21. We acknowledge that just adding and subtracting the mean data involve much assumptions and inaccuracy, however, this calculation provides an empirical basis to support my PRS hypothesis.

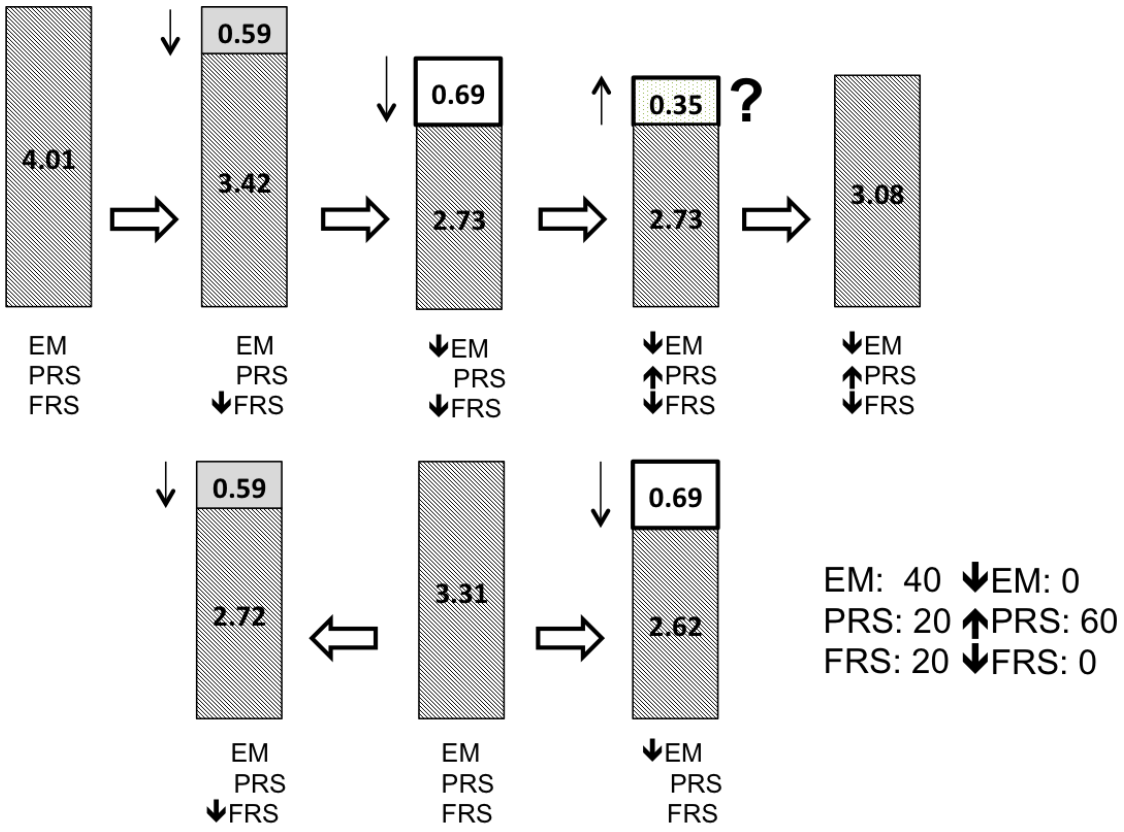


Figure 21: Illustration of motivation of experiment two from previous experiments.

5.3 Materials and apparatus

Experiment two used the same apparatus as in Experiment one except that it did not use the eye tracker VT1. Apparatus included: optokinetic drum, chin rest, FASTRACK system, EOG 100C, a camera to verify that subjects' heads were stabilized on the chinrest and several computers to generate stimuli or receive data from other machine. Readers can refer to Chapter 3 for details of the apparatus. The stimuli patter of optokinetic drum was slightly different from Experiment one, and it will be explained in next sub-section.

5.4 Methods

5.4.1 Design of experiment

The most difficult challenge of this experiment was to control EMv and PRSv to be the same in all conditions while manipulating the PRSv to be different for different conditions. Before designing the experiment, there were two questions to be answered first: (i) what level of EMv should be used? And (ii) how to manipulate EMv and FRSv to be the same across different conditions? To answer the first question, a literature review was conducted to find the most common and strongest VIMS provoking condition. Results indicated that when the stimuli velocity was at 60 dps along the yaw axis, the highest levels of VIMS were reported in many previous studies (Stern, 1990; Hu, 1989; Guo, 2011; Yang, 2011). When viewing a stimulus moving at 60 dps, the average EMv of the viewers was around 40 dps and the average FRSv was around 20 dps. Therefore in Experiment two, EMv and FRSv were controlled to be the same as in this condition (i.e., EMv of 40 dps and FRSv of 20 dps).

In this experiment, a moving cross, oscillating periodically from 17.1 degrees to the left of the center of the screen to 17.1 degrees to the right of the center at 60 dps was used to control EMv and FRSv. Subjects were asked to look at the moving cross. This oscillation amplitude of the moving cross was also used in condition A of Experiment one. Results of pilot tests indicated that viewing this moving cross would generate EM patterns similar to the OKN evoked when watching a visual stimulus moving at 60 dps along the yaw axis. Further pilot tests showed that, under this setting, subjects would produce an average EMv of 40 dps and FRSv of 20 dps regardless of changes in the stimuli velocity. Using this method, PRSv can be independently manipulated from EMv and FRSv.

There were 3 levels of PRSv: 10 dps, 20 dps and 60 dps. They were achieved by carefully manipulation of EM and stimuli velocity. Since EMv in all conditions was 40 dps, stimuli velocities were set to 50 dps, 60 dps and 100 dps, respectively to achieve the required levels of PRSv. I found that when stimuli velocity was as high as 100 dps, viewers could see flickering generated by aliasing. This problem was solved by using a smooth sine wave gradient to transit between the black and white edges in the stripe patterns (see Figure 22). The cycle length of the sine wave equals to the total width of black and white stripes in experiment one. In other words, no change to the spatial cycle length. A pilot study on comparing VIMS under these two types of patterns was conducted on the same group of subjects participating Experiment two. Results indicated that there was no significant different between them although the mean values of VIMS using the original black and white stripes were slightly higher than that using a gradient. There was also no significant difference in the EMv generated by viewing the two types of pattern.

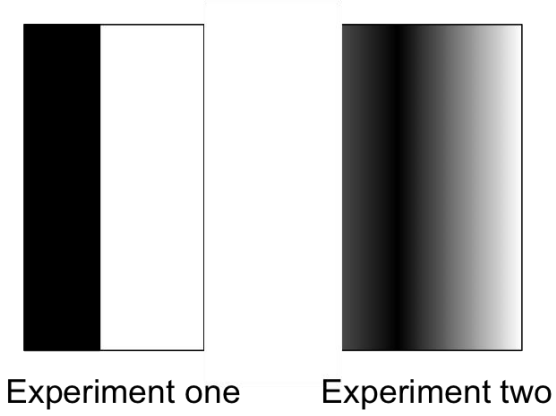


Figure 22: One cycle of stimuli patterns in experiment one and two

The four conditions used in Experiment two are illustrated in Table 8 and Figure 23. The moving cross in Conditions A, B and C was draw in the center of a black ellipse of the same size as the one used in Experiment one. Both the cross and the ellipse moved synchronously. The ellipse was added so that the visual stimuli shown to the subjects in both Experiments one and two were as similar as possible. In condition D, a stationary ellipse and a cross was drawn on top the screen, but subjects were instructed not to view on them. In so doing, the stimuli shown in this experiment matched what was shown in Experiment one as much as possible.

Table 8: “Bv” stands for background velocity, “Cv” stands for visual target velocity

Con.	PRSv °/s	Bv °/s	Cv °/s	EMv °/s	FRSv °/s
A	10	50	60	40	20
B	20	60	60	40	20
C	60	100	60	40	20
D	20	60	NA	40	20

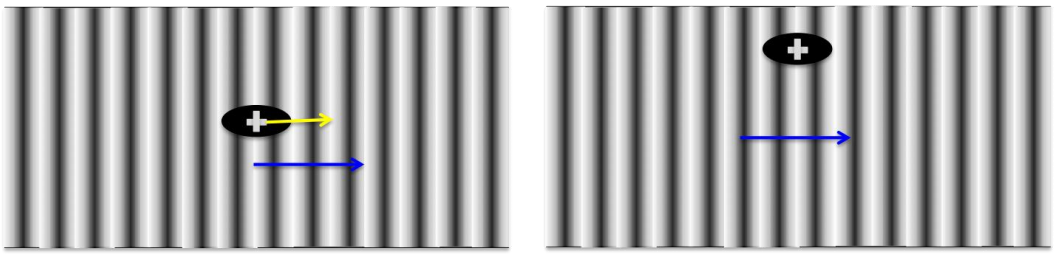


Figure 23: illustration conditions in Experiment two

Similar to Experiment one, within subject design was also used in this experiment. The order of presentation of test conditions to each subject was randomized. Fourteen subjects, 7 males and 7 females, with ages from 24 to 29, participated in the experiment. All of them were students at the Hong Kong University of Science and Technology. They were tested to have normal or corrected-to-normal visual acuity. Subjects’ written consents were obtained and they received a compensation of HKD50 (about USD6) per hour for their time. The experiment was approved by the Human and Ethics Committee at the Hong Kong University of Science and Technology. In case a subject did not feel well on the day of experiment, he or she was required to have a rest and come back on another day.

The dependent variables and other measurements were the same as Experiment one: VIMS levels were measured using the 7-point nausea ratings, ratio scale nausea data with free modulus magnitude estimation and SSQ. Vection rating, eye motion along horizontal and vertical directions as recorded by EOG 100C, BIOPAC® as well as subjects’ body movements as recorded by FASTRAK system were also measured. Details on how the EM and body movements were measured are documented in Chapter 4.

5.4.2 Procedure

The procedure of experiment was similar to that of Experiment one. Before the experiment, visual acuity tests and line length estimation tests were conducted. During each condition, the following tasks were performed in sequential order: (i), fill in pre-SSQ; (ii), place electrodes on subject's face for EOG measurement; (iii), put on the belt mounted with the Polhemus FASTRACK position sensor; (iv), conduct calibration runs to map EOG voltage to EM magnitude in degrees; (v), a 5-minute rest; (vi), the 30-minute exposure and in ever 2 minute interval, subjects reported nausea ratio scale rating, 7-point nausea rating and vection rating; (vii), immediately affect the exposure, subjects filled in the post-SSQ. For each subject, consecutive exposures were separated by at least one week to minimize the effects of adaptation.

5.5 Statistical results

I. Correlation between different measurements

Pearson correlation test showed that the average 7-point nausea rating during 30 minutes significantly correlated with average vection ratings, average ratio scale nausea ratings and SSQ total scores in all four conditions ($p < 0.05$). Vection ratings and ratio scale rating had weak correlations with other measurements ($p > 0.05$). SSQ total score and sub scores had significant correlations with each other and with average 7-point nausea rating ($p < 0.05$) in al four conditions, and weak correlations with ratio scale nausea ratings and vection ($p > 0.05$).

II. Eye motion data

The average eye motion velocities in condition A to D were: 36.05 dps, 38.22 dps, 37.36 dps and 34.39 dps. There no significant difference among eye motions in the four conditions ($p > 0.05$). Hence eye motion and foveal retinal slip velocity were verified to be controlled the same across all conditions. Calculation of eye motion velocities can be found in the appendix, which was the same as what used in experiment one.

III. Main effect plots

Average 7-point nausea rating in 30 minutes in control condition (D) was significantly lower than condition C, where peripheral retinal slip velocity was 60 dps ($z = -2.133$, $p = 0.033$). Average ratio scale nausea rating in 30 minutes in condition A, where peripheral retinal slip

velocity was 10 dps, was significantly lower than condition C (z = -2.417, p = 0.016). There was no other significant difference among the measurements (Figure 24, Figure 25). However, for most measurements, a trend that VIMS increases as peripheral retinal slip velocity increases from 10 dps to 60 dps can be observed.

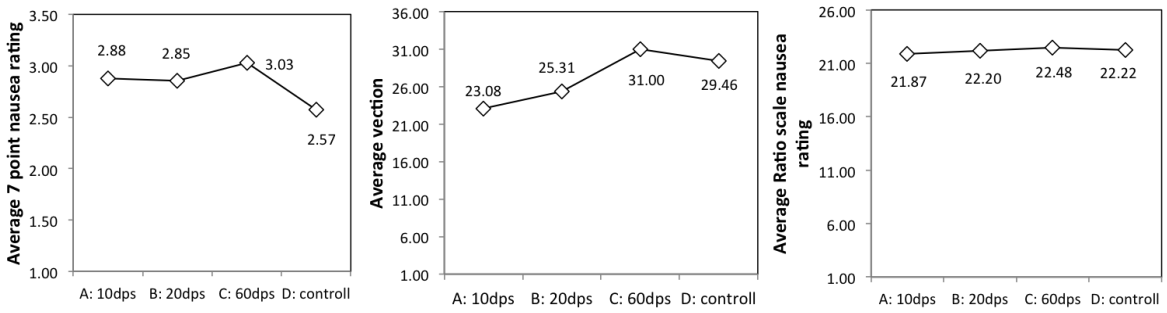


Figure 24: Average 7-poain nausea rating, average vection rating, average ratio scale in nausea in 30 minute exposure

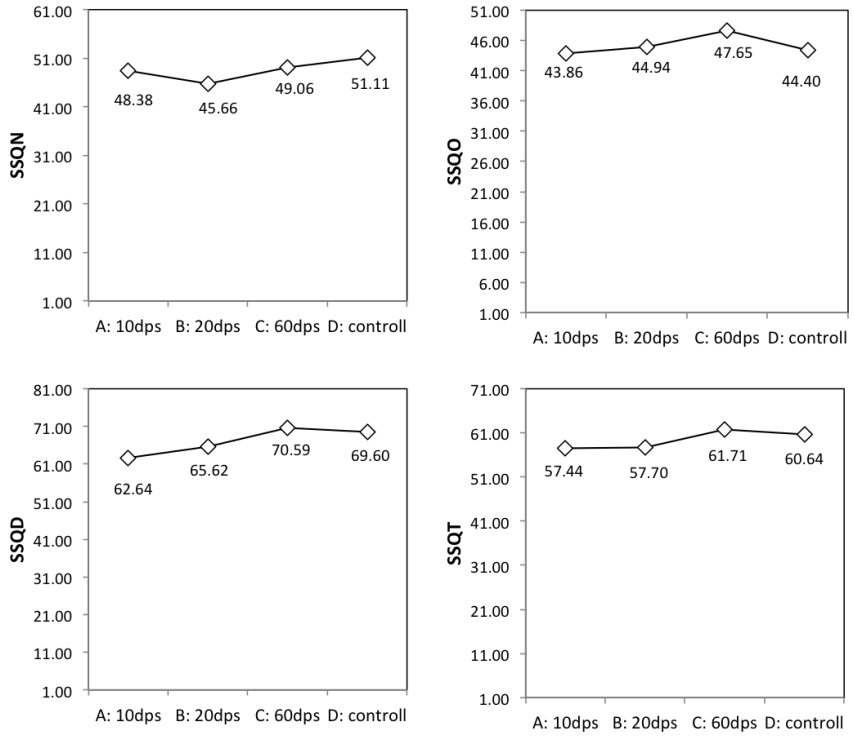


Figure 25: post SSQ nausea score, SSQ oculomotor score, SSQ disorientation score and SSQ total score

IV. Time course effect

The average 7-point nausea rating of all subjects were calculated in every 2 minutes (Figure 26). In most of the time, condition C has higher 7-point nausea than other conditions, and

condition D has lower 7-point nausea than other condition, but there was no significant difference.

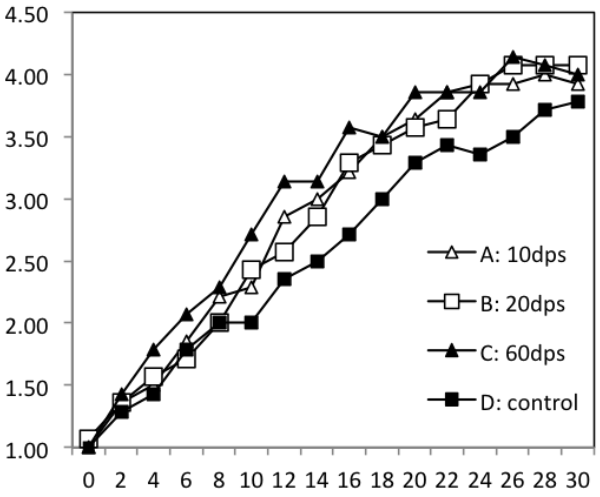


Figure 26: Average 7-point nausea rating of 14 subjects in every 2 minutes in 30 minutes exposure

In Table 9, time for each subject took to reach level 4 "mild nausea" of 7-point nausea rating was listed. Number of subjects who reach level 4 at of before 30th minute was 6, 7, 8, 7 for condition A to D respectively. There was no significant difference among "time to level 4" in the four conditions by Wilcoxon test ($p > 0.05$). However, a weak trend that it took subjects shorter time to reach level 4 in condition C than in other conditions.

Table 9: Time to reach level 4 of 7-point nausea rating

SbjNO.	A: 10dps	B: 20dps	C: 60dps	D: control
1	>30	10	>30	>30
2	>30	>30	16	>30
3	>30	>30	>30	30
4	>30	>30	>30	>30
5	>30	>30	>30	>30
6	>30	>30	20	>30
7	6	8	8	6
8	14	14	6	14
9	22	28	10	20
10	>30	>30	>30	>30
11	12	16	6	6
12	12	8	12	12
13	>30	>30	>30	>30
14	12	20	24	26

V. Body motion data

The average standard deviation of the body movement of 14 subjects in the three axes during the 30-minute exposure was analyzed. The SDs range from 0.3141 cm to 0.5432 cm, which indicated that all subjects could keep stable during experiment. There is no significant difference among the 4 conditions on the same axis.

5.6 Conclusion and discussion

Statistical results showed that VIMS did not significantly increase as peripheral retinal slip velocity increases from 10 dps to 60 dps when eye motion was around 40 dps. Only ratio scale in nausea in 60 dps was significantly higher than that of 10 dps ($p < 0.05$), and the mean values of VIMS increased as peripheral retinal slip velocity increased. This result contradicts with result when eye motion is suppressed, where VIMS increases as peripheral retinal slip velocity increases. One explanation for this could be that conditions with eye motion of 40 dps already provoke almost the strongest VIMS. Due to the ceiling effect, even increasing peripheral retinal slip velocity from 10 dps to 60 dps did not change too much. Another explanation is there could be an interaction between eye motion and peripheral retinal slip that effect of latter to VIMS becomes smaller as the former increases (Figure 27). To justify the first explanation, data of subjects who had reached level 4 of 7-point nausea rating before experiment ended in condition A was eliminated. For the remaining data, all standard statistical tests were conducted. However, there was still no obvious difference among the first three conditions. This increases the possibility of our second explanation.

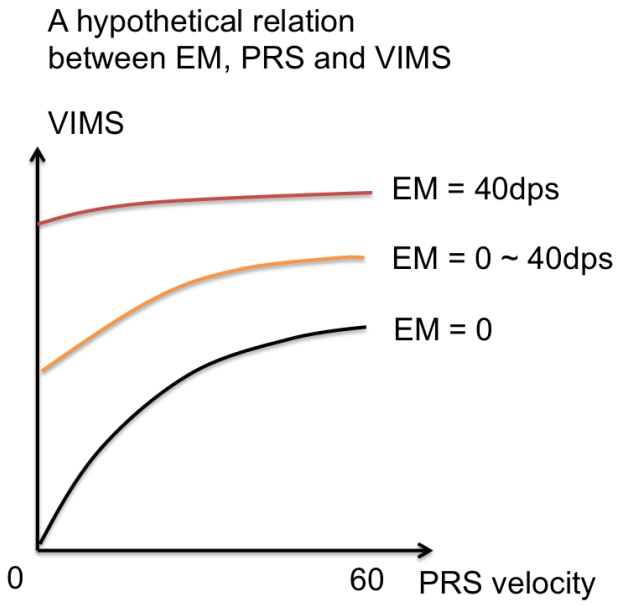


Figure 27: illustration of possible interaction between peripheral retinal slip and eye motion

So the question is, what dose peripheral vision's effect to VIMS? Is it as strong as eye motion? Since peripheral vision is critical to sense of motion, and only senses of motion for visual system and vestibular system contradict with each other that VIMS can be produced, therefore peripheral vision may act as a switch of VIMS. This includes two parts of understanding: first, if peripheral vision is not blank and gives motion signals, then what is more important to VIMS would be eye motion; second, if peripheral vision is blank and gives no hints on motion, even eye motion is as high as 40 dps, there may not be VIMS. This could be a direction of future study on VIMS.

Chapter 6 Experiment three and four: visually induced motion sickness during computer game playing and reviewing

6.1 Motivation

With the development of virtual reality (VR) technique, incidences of VIMS when watching movies, VR simulation or computer games have been reported in recent years. Over eighty percent of individuals exposed to VR simulations for 20 minutes reported increases in sickness symptoms (e.g., Cobb *et al.* 1999; Kennedy and Stanney, 1998; Lo and So, 2001; So *et al.*, 2001; Wilson *et al.*, 2000). Incidents of VIMS have also been reported among users of various immersive video game systems, such as Xbox, PlayStation, and Wii (e.g., Merhi *et al.*, 2007; Stoffregen *et al.*, 2008). No doubt, the occurrence of VIMS can reduce the joy of entertainment. More importantly, efficiency and accuracy of performance can be reduced in scientific applications of VR technology. Hence, research to study factors affecting VIMS is desirable and meaningful. In 2005, ISO held an International Workshop Agreement 4 (IWA4) in Tokyo on image safety. The workshop was actively participated by representatives from the game industry. At the end of the workshop, a call to continue to study and reduce symptoms of VIMS among computer game players was made (So and Ujike, 2010).

The presence of eye motion had been shown to increase VIMS in many studies (e.g., Ji *et al.,* 2009; Yang *et al.,* 2011), as well as Experiment one. However, eye motions in these studies were provoked by watching rotating striped patterns on optokinetic drums. Studies related to eye movements and their effects on VIMS during game playing could not be found. In other words, although eye fixation has been shown to significantly reduce VIMS when watching rotating drums, whether such an effect could also be applied to reduce levels of VIMS among players of computer games is not known. If, indeed, eye fixation can be verified to reduce VIMS among game players, it would provide a way to design a VIMS-reduce computer game. Hence the primary objectives of Experiments three and four were (i) to study the eye motion during computer game playing and (ii) to verify whether eye fixation can reduce eye motion and levels of VIMS.

Besides EMs, active and passive controlling of a game were also introduced as another factor

in my experiments. The sensory rearrangement theory explains that motion sickness is likely to occur when there is conflict among signals coming from different sense organs, or when there is conflict between real and expected forms of these signals (Reason, 1978). Since the "conflict" as defined in the theory is a neural psychological signal that is difficult to quantify, direct verification of this theory can be difficult. However, its ability to describe situations that can provoke motion sickness has been widely accepted. One such example is that a taxi driver should experience less motion sickness than the passengers (Rolnick and Lubow, 1991). The drivers executed a planned series of vehicle rotations and the passengers just watched and experienced the motion. Results showed that those who had controls of the rotations reported less symptoms of motion sickness than those who just experienced the motion. Theoretically, the drivers had "less" conflict between the perceived motion and the "expected" motion. Xiao *et al*. (2011) extended the hypothesis to see whether the "control effect" was just limited to physical motion or could be extended to visual motion. One group of subjects drove (the driver) a computer driving simulation game and another group of subjects watched the video (the passenger). Results showed that the influence of control on motion sickness incidence is not limited to vehicle controls. It can also be applied to the control of virtual environment and games. However, EM was not studied in that experiment. Given the importance of EM in the generation of VIMS (e.g., Ebenholtz et al., 1994, Ebenholtz, 2001; Hu *et al*.; Ji *et al.*, 2009; Yang *et al.,* 2011; Guo *et al.*, 2011) and the potential influence of active and passive game playing, we hypothesized that (i) EMs of active and passive gaming are different and (ii) this differences are related to the rated levels of VIMS.

6.2 Objective and hypothesis

The objectives of Experiment three were: (1) to compare VIMS levels between subjects who were actively playing computer games and subjects who were passively watching recorded videos; (2) to compare EMs under these two modes of playing; and (3) to study effects of eye fixation on VIMS during active game playing. The objectives of Experiment four were: (1) to study types of EM during passive viewing conditions; and (2) to investigate whether eye fixation can reduce VIMS during passive viewing conditions. VIMS levels provoked by passive watching are hypothesized to be higher than those provoked by active game playing (the game hypothesis I), and VIMS levels are hypothesized to be reduced by eye fixations (the

game hypothesis II).

6.3 Methods

6.3.1 Design of experiment

The video game entitled ‘Mirror’s Edge’, developed by EA Digital Illusions CE (DICE) was used in our experiment. Mirror’s Edge is a single-player first person action-adventure video game allowing for a wide range of actions. Players enjoy great freedom of movement. In this study, subjects used mouse and keyboard to control the avatar in the game from a first-person perspective (Figure 28). Due to rapid visual motion involved in the game, players have reported incidences of motion sickness (http://forums.steampowered.com/forums/showthread.php?t=1683987).

Figure 28: A screenshot of the game used in Experiment three and four, Mirror’s Edge

Nine males and nine female participated in Experiment three and two males and seven females, participated in Experiment four. In Experiment four, we could have done more subjects, however, students in the university were taking final exams and it was not easy to recruit many subjects. Actually our results later showed significant and consistent with previous conclusion on eye motion and VIMS. All of the subjects were undergraduate

students or postgraduate students at the Hong Kong University of Science and Technology. They all signed subject consent forms and passed visual acuity tests before participating the experiment. They received money compensation of 50 HKD/hour. In case a subject did not feel well on the day of experiment, he or she was required to have a rest and come back on another day. The experiments had been approved by the human subject committee of the Hong Kong University of Science and Technology. Before the experiment, all subjects were asked to fill in the motion sickness susceptibility questionnaire (MSSQ)(Golding, 2006).

Experiment three used a within-subject design with 3 conditions: (A) active game playing with no eye fixation; (B) active game playing with eye fixation; and (C) passive viewing of recorded videos of game playing with no eye fixation. Each consecutive exposures were separated by at least 7 days to minimize effects of adaptation. A training session was conducted a week before the first condition to help the participants to be familiar with the control of the game. A passing criteria was set so that all participants were able to attain the same miles stone. The time to complete this passing criteria (a particular pre-determined stage of the game) was recorded as the "time to familiar the game". In order to balance the order of presenting the active and passive viewing condition, the 18 participants were randomly divided into 2 groups. The video that subjects watched in the passive viewing condition were recorded by another subjects during their active game playing conditions. I have been very careful in setting up a procedure that matched the game playing styles between the viewers and the players. In particular, the frequencies of pressing navigation keys during the training sessions were recorded to classify participants into "fast" moving players and "slow" moving players. In this study, a "fast" player would watch recording from another "fast" player during the passive viewing conditions. Similarly, a "slow" player would watch recordings taken from another "slow" player playing the game. In Experiment three, all 18 participants took part in all three conditions. Similarly, Experiment four also used within subject design. It had two conditions: (A) passive watching without eye fixation; and (B) passive watching with eye fixation.

6.3.2 Material and apparatus

The procedures and apparatus used in Experiments three and four were the same. The game was running in a computer with Windows 7 Enterprise System and a 27-inch LCD monitor 50 cm away from subjects' eyes. During the exposure, all the background light was turned off.

Subjects' eye motions were measured by an eye tracker VT1 produced by Eye Tech Digital System (Figure 29). The voice of the game was muted.

Figure 29: A photograph of the experimental setup of Experiments three and four

6.3.3 Procedure

During each game session (i.e., exposure), participants were required to place their heads on a chin-rest to minimize head motion (Stoffregen and Smart, 1994). At the beginning of each session, each subject went through the calibration of the eye tracker and filled in a pre-exposure SSQ. Subjects were then exposed to the respective conditions according to a pre-randomized presentation order. During the 30 minutes exposure, rated levels of nausea were measured using a 7-point nausea rating adopted from Golding and Kerguelen (1992) at every five minutes. Each player's performance in terms of mouse position and keystrokes was recorded by software named Macro Recorder, and their screenshot of playing were recorded in the form of "avi" video by software named PlayClaw. Also, their head positions were monitored by a webcam to verify that whether they did rest their heads on the chin-rest. After the 30-minute exposure, all participants were instructed to fill in the post- exposure SSQ.

6.4 Results

6.4.1 Analysis of rated level of VIMS

I. Experiment three

Results of Pearson correlation tests indicated significant correlation relationships between post-SSQ total score and 7-point nausea rating in all three conditions: condition A, *Pearson Corr.* = 0.501, p = 0.034; condition B, *Pearson Corr.* = 0.651, p = 0.003; condition C, *Pearson Corr.* = 0.703, p = 0.001.

In the MSSQ, a question asked the subjects to self-assess their motion sickness susceptibility (Table 10). Interestingly, the "time to familiar the game" significantly correlated with the subjects' susceptibility to VIMS (*Pearson Corr.* = 0.53, p = 0.02, Figure 30). Since all subjects had no experience of 'Mirror's Edge' before the experiment, subjects who took less time to get familiar with the game could be those who had experience in other computer games. The correlation results suggested that they had lower susceptibility than those who took longer time to familiar with the game. Such a correlation might have been due to those who were susceptible to motion sickness would refrain themselves from playing computer games. Another possible reason might be due to adaptation effects. In other words, those who play computer games all the time might have adapted to stimuli resulting in lowering of their susceptibility to sickness. Although previous experience in Mirror's Edge was well controlled in our study, relevant experience to other computer game could introduce cofounding effect to the result. Hence part of the data analysis later on will specifically deal to this problem.

Table 10: Motion susceptibility survey

In general, how susceptible to motion sickness are you?
1. Not at all
2. Slightly
3. Moderately
4. Very
5. Extremely

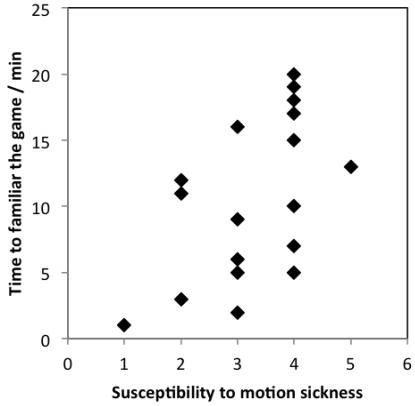


Figure 30: time to familiar the game vs. susceptibility to motion sickness

Surprisingly, we found no significant difference among the three conditions by Wilcoxon signed rank test on both the SSQ total scores and the average 7-point nausea ratings (Figure 31). Further investigation indicated that both SSQ total scores and 7-point nausea ratings increased with exposure durations ($p<0.05$, Wilcoxon comparing pre- and post-SSQ data and Friedman two-way ANOVAs on effects of exposure duration on nausea). This suggests that the stimuli did cause sickness in the subjects but the lack of significant effects of active/passive playing could be masked by other noise. One of the common source of noise in the study of VIMS has always been the susceptibility to motion sickness. In general, about 1/3 of the subjects were not susceptible to the sickness and their presence might have diluted any effects that we was looking for. To verify this, we divided the 18 subjects into two 9-subject sub groups using their "time to familiar". Since this time was correlated with their self-rated susceptibility to sickness, this effectively divided the subjects according to their susceptibility to sickness as well. In the group with low "time to familiar" and low sickness susceptibility, subjects experienced significantly higher 7-point nausea rating at 30th minute in passive viewing condition than active playing (z = -2.414, p = 0.016). There was no significant difference found in the other group. Once again, we were surprised by the finding as we were expecting to find a significant difference between active/passive in the group with higher sickness susceptibility rather than the opposite. Upon further investigation, we found a possible explanation. There might have been a 'ceiling' effect in Experiment three, As the games did cause much sickness, those who were highly susceptible to sickness felt sickness regardless of whether they were actively playing or passively viewing the games.

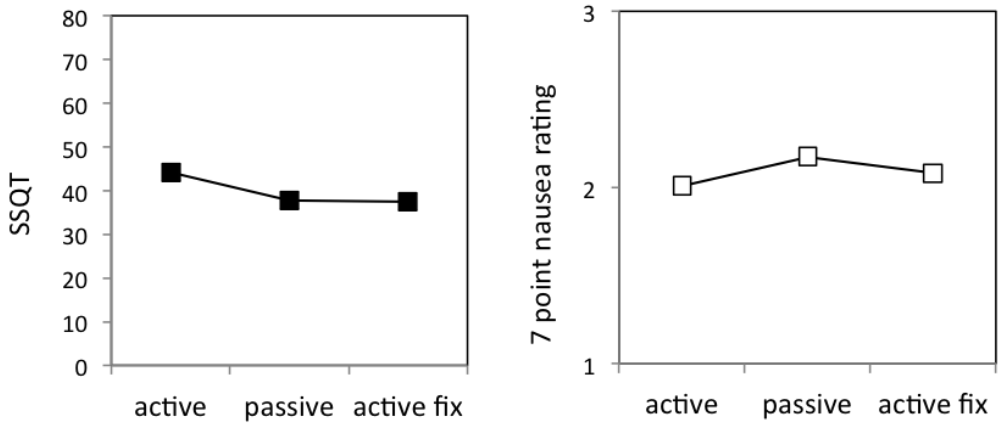


Figure 31: post SSQ total score and 7-point nausea rating in different conditions

We were disappointed to find that eye fixation did not significantly reduce levels of VIMS among players actively playing the games. When we analyzed the eye position data, we found

that the use of an eye fixation marker did not significantly reduce EM. This suggested that the use of eye fixation marker is not effective in reducing levels of VIMS in game playing because it could not reduce EM.

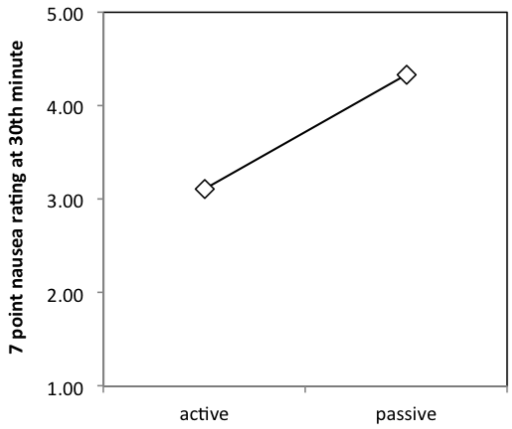


Figure 32: 7-point nausea rating at 30th minute for subjects who ranked from NO. 1 to NO. 9 in time to familiar the game (lower time)

II. Experiment four

Before reporting the results of Experiment four, let's recap the findings of Experiment three before Experiment four was an extension of Experiment three. In Experiment three, subjects with lower susceptibility to sickness, reported significantly higher levels of VIMS when they were viewing the games passively than playing the games actively. However, the effects of eye fixation did not result in significant changes in levels of VIMS. The lack of changes in VIMS was associated with of lack changes in EMv. One obvious reason was that subjects needed to play the games and they would need to make Ems despite instructions to fixate on the eye fixation marker. Since the reduction of VIMS by suppression EM using an eye fixation marker had been a consistent and important finding (Stern, 1990; Guo, 2011; Yang, 2011), Experiment four was conducted. In this experiment, VIMS provoked by passively viewing a computer game with and without an eye fixation marker was studies. The post SSQ sub scores of nausea (SSQN) were significantly reduced from 40.4 to 27.1 by the addition of an eye fixation marker (z = -2.388, p = 0.017: Wilcoxon signed rank test). Similar trend was observed on other dependent variables such as 7-point nausea ratings but the effects were not significant (Figure 33).

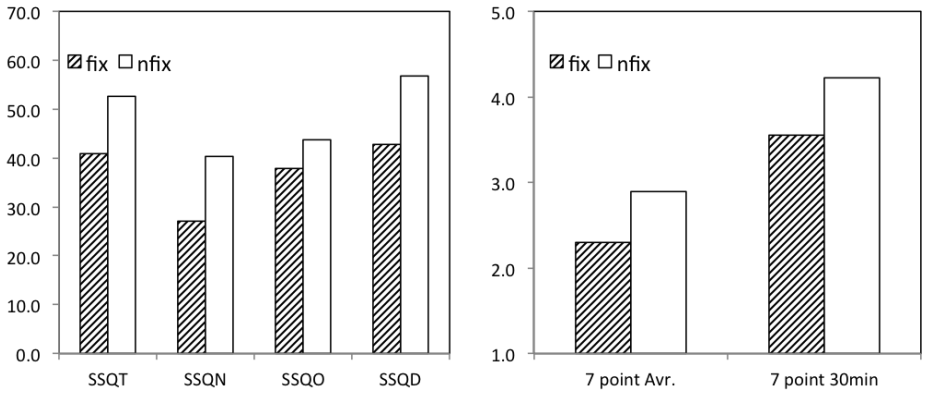


Figure 33: post SSQ scores and 7-point nausea rating in experiment four

6.4.2 Analysis of eye motion data

The eye tracker recorded both the left and right eye positions in terms of pixels. Based upon the individual calibration data, linear regressions were conducted to obtain the gaze positions in degrees using left and right eye data. Regression results showed that linear model was able to predict the gaze position, with left eye (x, y) and right (x, y) explained more than 95% of the variance ($R^2 > 95\%$).

For Experiment three, overall variance of EM during active game playing conditions and passive viewing conditions were statistically the same. We would like to remind the readers that participants did not watch their own recorded videos but videos recording of another game players with similar playing styles. For the active game playing condition with eye fixation, which was supposed to suppress eye motions, no significant reduction in variance of eye motion was found. This indicated that even with an eye fixation pointer placed at the center of the screen and with instructions to fixate ones' eyes, it was difficult to fixate ones' eyes while actively playing the game.

For Experiment four, eye fixation significantly reduced EM in both horizontal and vertical directions. A Matlab program was run to identify the occurrence, in terms of duration, of three main phases of EMs: durations of (i) fixation (EMv <=2dps), (ii) smooth pursuit (EMv <=40dps and >2dps) and (iii) saccadic EM (EMv > 40dps). On average, 62% of the time, EM was categorized as "fixation", 37% of the time categorized as "smooth pursuit" and no more than 1% of the time categorized to "saccadic". Scatter plots about SSQ total scores versus duration of stop, smooth pursuit and saccadic motion are listed in Figure 34. Although no overall significant correlation was found, trends could be observed for the duration of smooth

pursuit EM to be related positively with total SSQ score (the 2nd plot of Figure 34) while the total fixation time and total saccadic time negatively related to total SSQ score. This is consistent with past findings because the more one fixates one's eyes, the more it can help to reduce sickness, and the more one performs OKN-like eye motion, the easier he/she gets sick.

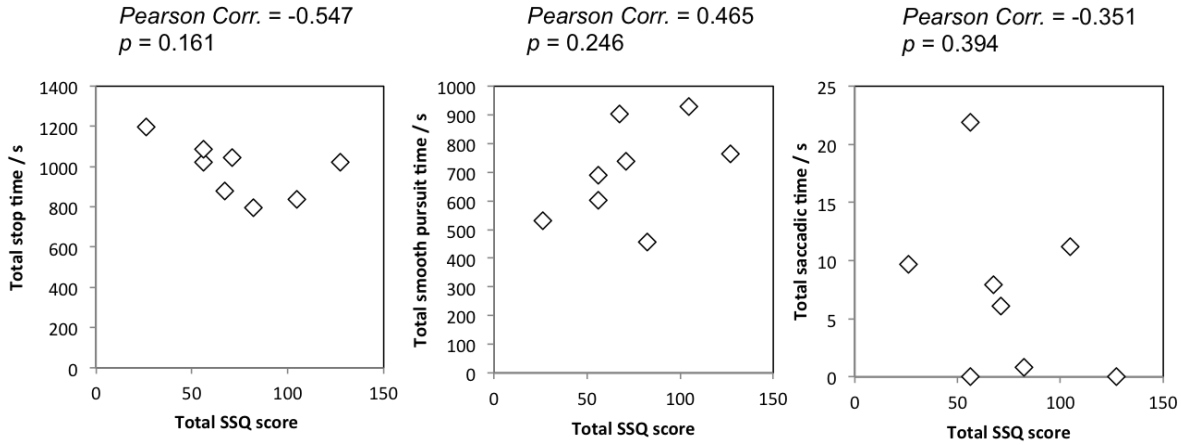


Figure 34: total stop time, smooth pursuit time and saccadic time versus SSQ score

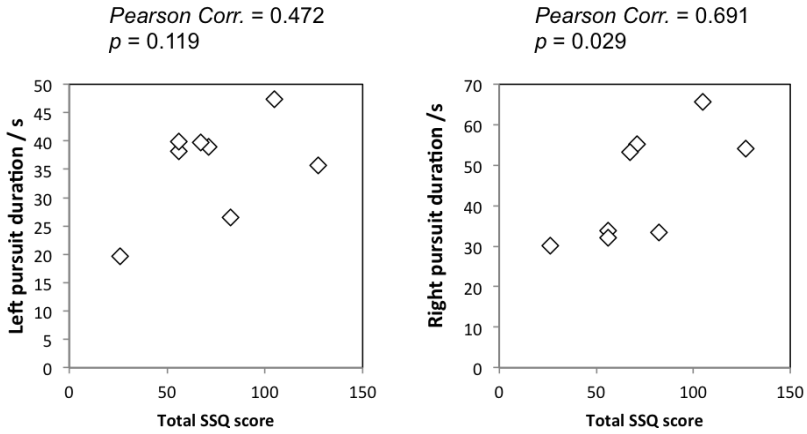


Figure 35: left pursuit and right pursuit duration versus SSQ score

Smooth pursuit EM was further divided into left pursuit and right pursuit. EM was categorized as left pursuit if the video scene was moving to the left and at the same time the horizontal eye motion was moving from right to left. The moving direction of the video scene was obtained by analyzing the keyboard record when the other subject was actively playing the game and recording this video. There were four directional controls for the game players to use: W (forward), A (leftward), S (backward) and D (rightward). When a subject pressed and held 'D', it meant that he/she was going right, and the scene displayed to the subject who passively watched it was actually moving to the left. Similar definition was used on right pursuit. Figure 35 illustrates the correlation between total SSQ score versus left pursuit and

right pursuit duration. Total SSQ score significantly positively correlated with the right pursuit duration (*Pearson Corr.* = 0.691, $p = 0.029$).

6.5 Conclusion and discussion

Difference in VIMS was not obvious between active and passive conditions for the whole group, while VIMS in passive condition was significantly higher than active condition for subjects who took shorter time to get familiar with the game. These subjects generally have more computer game experience and lower susceptibility to VIMS. For the subjects with higher susceptibility to VIMS, no difference in levels of VIMS was found between active playing and passive viewing. One explanation is the ceiling effect, those with higher susceptibility to motion sickness had been sickness regardless of whether they were actively playing or passively viewing the games.

Adding an eye fixation marker cannot reduce eye motion when the subject is actively playing the game. This indicates that adding a rest frame or some fixations in addition to the game video may have little benefit in influencing the EMs of the active players. On the other hand, adding an eye fixation marker can significantly reduce EM of the subjects who are passively watching the game. Such reduction of EM has been shown to be associated with significant reductions of VIMS in terms of SSQ nausea sub scores. Although trends of reducing sickness with the use of eye fixation markers were also observed in rated nausea levels, those trends were not significant. This suggests that the effects of eye fixation on reducing levels of VIMS was not as strong as previously reported in laboratory experiments (Stern, 1990; Guo, 2011; Yang, 2011). Further investigation of patterns of EMs during passive viewing of game video provides a reasonable explanation. According to the analyses of the duration of different types of eye motions, during passive viewing, subjects tend to relax their eyes on some fixation points for most of the time, and only 37% of time was spent in pursuing. In Experiments one and two, subjects spent nearly 100% of the time on OKN. Consequently, we can conclude that EM in Experiment 4 was about 60% less frequent then in Experiments one and two, therefore their suppression would not result in a very strong reduction of VIMS. We also found that duration of right pursuit significantly correlated with the SSQ total score. This indicated that subjects could experience higher VIMS if they perform more pursuit tasks. EM's importance on provoking VIMS has been further supported.

We admit that research on reducing VIMS of a game by changing its design is controversial, because a computer game's ultimate purpose is to entertain people. However, if we can develop a methodology to evaluate and predict a computer game's potential to provoke VIMS, without conducting a full experiment, it may be a helpful feedback to the game developers. Development towards such a methodology will be introduced in the next chapter.

Chapter 7 Regression analysis on effects of eye motion velocity (EMv), foveal retinal slip velocity (FRSv) and peripheral retinal slip velocity (PRSv) on VIMS

7.1 Motivation and objective

In Experiments one and two, effects of EMv, FRSv and PRSv were studied. The results indicated that both EMv and FRSv can significantly affect levels of VIMS. For PRSv, although the results of Experiment two showed that it did not significantly affect levels of VIMS in the presence of EM, in previous studies (JI, 2009; YANG, 2011), PRSv was found to significantly affect levels of VIMS when EM was suppressed. Therefore we were interested in how the combinations of these three factors could affect the levels of VIMS. It would be very useful and meaningful if we could develop a mathematical model to predict levels of VIMS to be provoked by a certain visual stimulus with knowledge about these three stimulus-dependent factors. Furthermore, these three factors: EMv, PRSv, and FRSv are objective rather than subjective. Even though they involve physiology depending on the visual stimuli, they are not psychological (hence, subjective) responses. Most important of all, they could be measured without make someone sick. In other words, we believe that for a sickness-provoking stimulus (e.g., a computer game), it would be possible to ask a few viewers or players to be exposed to the games. During the exposure, EMv and videos of the stimulus could be measured. Regional or global optical flow velocities could be extracted from the videos which can then be used to calculate FRSv and PRSv (Kiryu, 2007). While it is outside the scope of this thesis to document the algorithms to calculate regional and global optical flow velocities, it is the objective of this chapter to report a modeling effort to predict levels of VIMS based upon EMv, PRSv and FRSv.

In summary, the objective of this chapter is to develop a mathematical model to predict VIMS by EMv, FRSv and PRSv utilizing the data collected from our past studies. We humbly admitted that we were not the first one to develop model to predict levels of VIMS. Oman (1992) reported a Kalman filter type model to predict sensory conflict; So *et al.* (2001) reported a Cybersickness Dose Value (CSDV) to predict nausea based on spatial complexity

and visual velocity of a stimulus; and Kityu (2004) reported a model to predict levels of VIMS based on global optical velocity of the visual stimulus. However, none of the above model explicitly isolates the effects of EMv and FRSv.

7.2 Model

7.2.1 Definition

The model uses the 7-point nausea rating as the dependent variable (i.e,, the model output). EMv, FRSv and PRSv are used as the predictor variables. Since experiment data regarding 7-point nausea rating either indicated no interaction among some of the three factors within the ranges that we used, or the data till now was not enough to calculate the interaction effect, the model is based on multiple linear regression with slight modification to fit the ordinal nature of the dependent variable. Further study on more data are desirable.

$VIMS = min\ \{\text{Round}(e*EMv + f*FRSv + p*PRSv + c), 7\}$.

The expression "Round(X)" stands for the rounded integer of X. All three factors use unit degree per second (dps). Although 7-poaint nausea rating is an ordinal scale, it was treated as ratio scale in regression. Data have shown that the 7-point nausea ratings correlated with the ratio scale nausea data (see Chapter 4). Ratio scale nausea was not used as the model output because the ratio scale nausea data were collected using a free modulus method which meant that everyone were free to use a different baseline. Furthermore, while the ratio scale data were something that I had developed in my research, the 7-point nausea ratings had been a standard measurement of VIMS used by many different researchers (e.g., Golding and Kerguelen, 1992; Webb and Griffin, 2001, 2003, Ji *et al.*, 2009; Lo and So, 2001; Regan 1995; So *et al.*, 2001a,b). Estimations of coefficients *e, f, p* and *c* in the linear regression model $Y = e*EMv + f*FRSv + p*PRSv + c$. followed the standard ordinary least square (OLS) method (SPSS menu).

7.2.2 Predictor variables

I. Data sources

Data that were used to conduct the regression analyses came from 5 experiments: Experiments one and two mentioned in previous chapters and another three experiments, which were conducted under similar experimental setting (Yang and Guo *et al.*, 2011; Guo, 2011). The author was the sole or co-experimenter in all five experiments and all five experiments used the same apparatus. Total number of observed data session is 192. One data session represents data collected in a 30-minute exposure to a VIMS provoking stimulus. Combinations and the ranges of the values of the three predictor variables within the five experiments are listed in Table 11. The reasons why these five experiments were selected are: (i) they were conducted by at the same laboratory using the same apparatus; (ii) the author was the experimenter or the co-experimenter; (iii) the combinations and the ranges of predictor variables had been rich enough to conduct a meaningful regression; (iv) they all shared one common condition (about 40 dps EMv; about 20 dps FRSv and about 20 dps PRSv), Because EMv is a measured parameter, it could not be exact.

Table 11: Combinations and ranges of predictors

Source	EMv/dps	PRSv/dps	FRSv/dps
Exp 1	0	15	0
Exp 1	0	15	15
Exp 1	40	20	0
Exp 1	40	20	20
Exp 2	40	10	20
Exp 2	40	20	20
Exp 2	40	20	20
Exp 2	40	60	20
Exp A	0	60	0
Exp A	40	20	20
Exp B	0	40	0
Exp B	40	20	20
Exp C	0	7	0
Exp C	40	20	20

II Range of data and the scope of the model

In this modeling effort, the ranges of the EMv, FRSv and PRSv were 0 to 40 dp, 0 to 20 dps and 7 to 60 dps, respectively. Consequently, the scope of the model is set within these ranges. The maximum slow phase velocity of OKN has been reported to be near 40 dps(Watanabe *et al*, 1986), therefore EMv from 0 to 40 dps should have covered the entire range of EMs to be found in subjects watching typical VIMS provoking stimuli. The 20 dps FRSv occurred when a subject was watching a stimulus moving at 60 dps and exhibiting an OKN with slow phase

EMv of 40 dps. This condition (also referred to as the common condition) had been shown to produce the highest VIMS (Stern *et al.,* 1990; Ji *et al.*, 2009). The 60 dps PRSv was obtained when a subject was watching a stimulus moving at 60 dps but with eye fixation – a deviation from the common condition that has been shown to produce less sickness than the common condition (Stern *et al.*, 1990; Ji *et al.*, 2009). In summary, the ranges of the EMv had covered nearly the entire meaningful range of EMv while the ranges of FRSv and PRSv had covered the typical ranges that had been shown to produce levels of VIMS from little to the maximum.

7.2.3 Model outputs

I. Choices of model outputs

In all the five experiments, apart from the 7-point nausea rating, both SSQ scores and ratio scale nausea data were also recorded. Although SSQ scores well reflect all the possibility symptoms of motion sickness, it only records the level and symptoms of VIMS after 30-minute exposure, so it is not convenient enough if we want to study the average response during 30 minutes or the time course effect (like the survival analyses in Chapter 8). For ratio scale data, although it was recorded during the main test as 7-point nausea rating and also shown to be correlated with the 7-point nausea ratings, we found that the individual variability is very large because we allowed each subject to choose his or her own baseline. Consequently, we used the rated nausea levels taken from the 7-point nausea rating.

II. Ranges of model outputs and scope of the model

Output of the model has 7 levels: 1 ~ 7 and they ranged from (1) no symptom to (4) mild nausea to (7) moderate nausea want to stop. When the rated nausea levels were averaged, non-integer ranging from 1.0 to 7.0 are produced. Hence the output of the regression model $Y = e*EMv + f*FRSv + p*PRSv + c$ could be any positive integer. Consequently, we used the expression "Round()" and "*min* {}" to extract the final model output. We admit that the way that we treated the ordinal data as ratio data is not the best methodology for regression analysis in ordinal data, compared with methods like the ordered logit / probit regression (McKelvey *et. al*., 1975), but it dose provide a simple way to interpret the causality effect between VIMS and the factors

III. Normalization of nausea data to compensate the difference across the five experiments

Since the data were collected from different experiment, there could be some unknown noise that had caused the same condition in different experiments to provoke slightly different levels of nausea. The main source of noise has been the differences in subject groups. Although the nausea data obtained in the common condition from the five experiments were not significantly different, their means were not exactly the same either. In order to reduce the effects of this unknown noise, I normalized each data point according to the follow equations:

Normalized Y(i, j, k) = raw Y(i, j, k) / Avr_Common (j) * Avr_Common.

Y(i, j, k) stands for "subject i's 7-point nausea rating in condition k of experiment j". Avr_Common (j) stands for the averaged 7-point nausea rating in common condition of experiment j". Avr_Common stands for the average 7-point nausea rating for all subjects and all experiments.

We acknowledge that in terms of normalization, we could use dummy variable method to "normalize" the data. However, in our situation, since all five experiments were conducted in the same lab, using the same apparatus, and conducted under the supervision of the author, the main difference would be due to the randomness of subject. Consequently, our normalization procedure are used instead.

7.2.4 Procedure of model constructions

Average 7-point nausea rating during 30-minute exposure was used to fit the model and the model is to predict average VIMS during exposure. Three data preprocessing procedure were tried: using raw data without normalization; using normalized data; using normalized data, and taking average in each condition. Finally, sensitivity analysis was conducted for each factor.

7.3 Results

7.3.1 Regression analysis based on raw data

Table 12: Regression results for model using raw data

	Coefficients	t	Sig.
Intercept	2.454	9.763	< 0.001
EMv	0.001	0.059	0.953

FRSv	-0.001	-0.045	0.964
PRSv	0.012	1.948	0.054
R^2	3.1%		
Adj R^2	0.7%		

Regression results show that all three factors did not have significant effect (non-zero coefficients) on the response. This is clearly not correct because results of each individual experiment produce some significant effects of one or two individual factors on rated nausea levels (see Chapters 4 and 5, Yang and Guo *et al.* 2011; Guo, 2011). The lack of significant effects from the three predictor variables in Table 12 is because the variations among different subject groups in different experiment were larger than the main effects of the three predictor variables.

7.3.2 Regression analysis based on average raw data

Table 13: Regression results for model using average raw data

	Coefficients	t	Sig.
Intercept	2.433	7.726	0.001
EMv	0.000	0.042	0.968
FRSv	-0.001	-0.040	0.970
PRSv	0.013	1.628	0.164
R^2	58.9%		
Adj R^2	34.7%		

After averaging the raw data, the model using the three factors is still not able to describe the VIMS significantly ($p>0.05$). Although using average data can eliminate subjective variance within one experiment, the result indicates that experimental variation is needed to eliminate. Therefore normalization procedure is needed.

7.3.3 Regression analysis based on normalized data

Table 14: Regression results for model using normalized data

	Coefficients	t	Sig.
Intercept	2.353	8.634	< 0.001
EMv	0.015	1.562	0.12
FRSv	0.034	1.813	0.072
PRSv	0.009	1.383	0.168
R^2	35.6%		
Adj R^2	12.6%		

After normalization, all three factors still did not have significant non-zero coefficients ($p < 0.05$) but the R^2 has improved and the p-values have been reduced. One major known factor for the unexplained variance is the individual differences. Even though the normalization had equalized the noise introduced by the use of different subject groups among the five experiments, the major variances of inter-subject variability remained. In order to focus on the effects of the three predictors: EMv, FRSv and PRSv, the data of different subjects exposed to the same stimuli in the same experiment were averaged. This suggests a regression on normalized average data.

7.3.4 Regression analysis based on normalized average data

Table 15: Regression results for model using normalized average data

	Coefficients	t	Sig.
Intercept	2.351	19.722	< 0.001
EMv	0.014	3.718	0.014
FRSv	0.034	4.188	0.009
PRSv	0.010	3.107	0.027
R^2	97.4%		
Adj R^2	95.0%		

After averaged, the R^2 increases from 35.6% to 97.4% and adjusted R^2 increases from 12.6% to 95%. All three factors have significant non-zero coefficients. Both average normalized data (observation) and residuals are normal by Kolmogorov-Smirnov test (p>0.1, Figure 36, 37). Both residual versus EMv plot (1st plot in Figure 38) and residual versus FRSv plot (3rd plot in Figure 38) exhibit no discernible patterns, which indicates that the error term in the model is independent of EMv and FRSv. Plot of residuals versus PRSv shows that variance of residuals seems to reduce as PRSv increases. However, there is only one data point whose PRSv is 60 dps, therefore, this trend can not be confirmed at this moment. If it is, a quadratic term of PRSv may be needed.

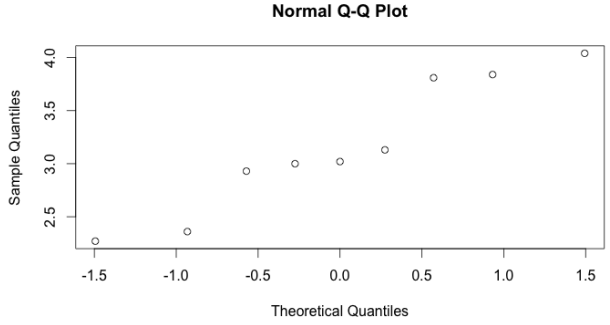


Figure 36: Q-Q plot of average normalized data

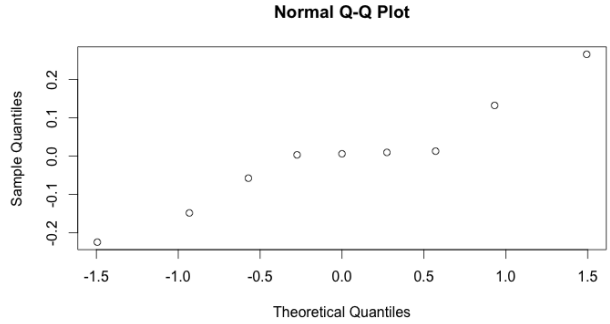


Figure 37: Q-Q plot of residuals of linear model in Table 15

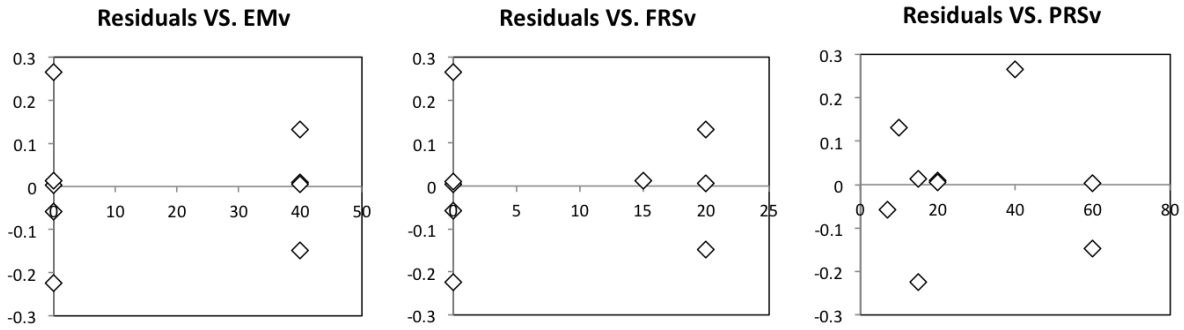


Figure 38: residuals versus eye motion velocity (EMv), peripheral retinal slip velocity (PRSv) and foveal retinal slip velocity (FRSv)

7.4 Interpretation and sensitivity analysis

The above results suggested the last model should be applied. The regression model is:

*Y = 0.014*EMv + 0.034*FRSv + 0.01*PRSv + 2.351.*

The final model therefore is:

VIMS = min {Round (*0.014*EMv + 0.034*FRSv + 0.01*PRSv + 2.351*), 7}.

When EMv, FRSv and PRSv all equal to 0, the output of the model is 2. This indicates that even the stimulus is static, after 30-minute's exposure, one could reach the 2nd level of 7-point nausea rating: any unpleasant symptoms, however slight. It makes sense because subject may feel fatigue hence unpleasant. This is supported by a previous experiment on static stimulus, which reported the average 7-point nausea rating in 30 minutes was 1.96 (JI, 2009). Another extreme case when EMv = 40 dps, FRSv = 20 dps and PRSv = 60 dps, the output is 4, which means "mild nausea". This combination is actually used in the regression and 4 is an

estimation of it. Table 16 illustrates by how much dose each factor increase to result in one unit increase in VIMS level. From this table, it seems the most important factor is foveal retinal slip velocity. However, we need to admit that eye motion and foveal retinal slip is not completely independent, especially the visual target's velocity is low. This means if you want to reach some level of foveal retinal slip velocity, non-zero eye motion velocity is a must.

Table 16: by how much dose the three factors increase to result in one unit increasing of VIMS

	EMv	FRSv	PRSv
VIMS level increases by 1	71 dps	29 dps	100 dps

I. Contributions of Eye motion velocity (EMv) on model outputs

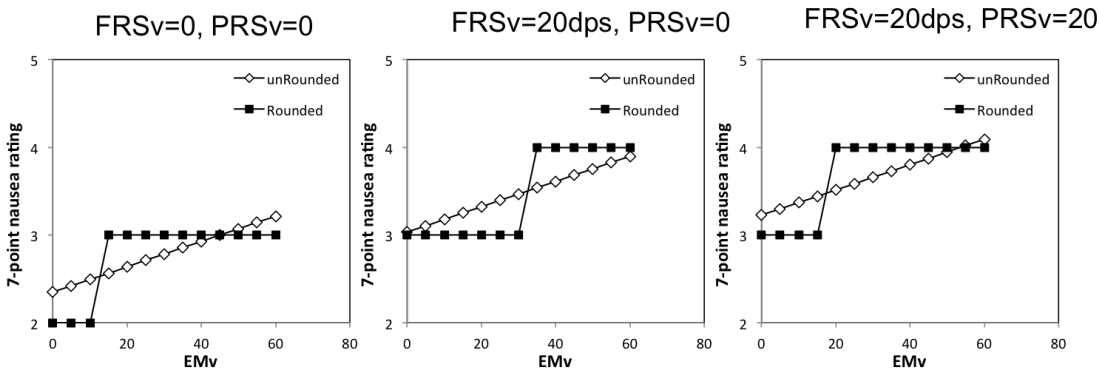


Figure 39: changes of model output on changes of eye motion velocity. In each plot, FRSv and PRSv are fixed.

II. Contribution of Foveal retinal slip velocity (FRSv) on model outputs

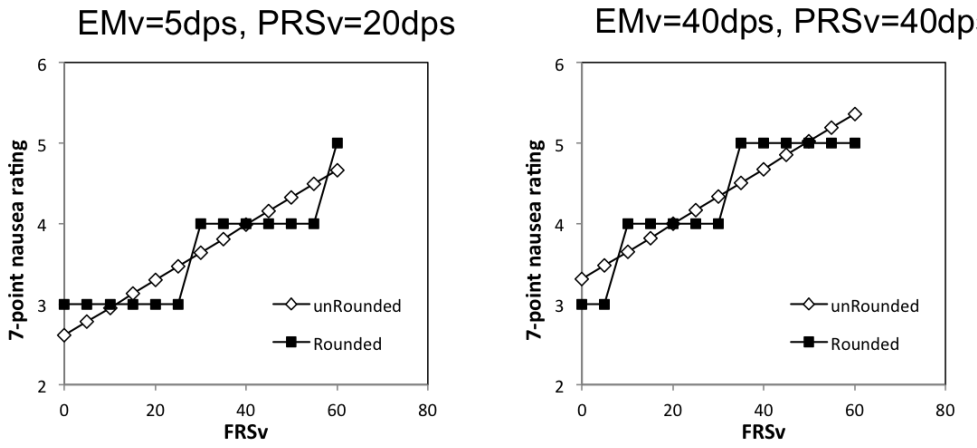


Figure 40: changes of model output on changes of foveal retinal slip velocity. In each plot, EMv and PRSv are fixed.

III. Contributions of Peripheral retinal slip velocity (PRSv) on model ouputs

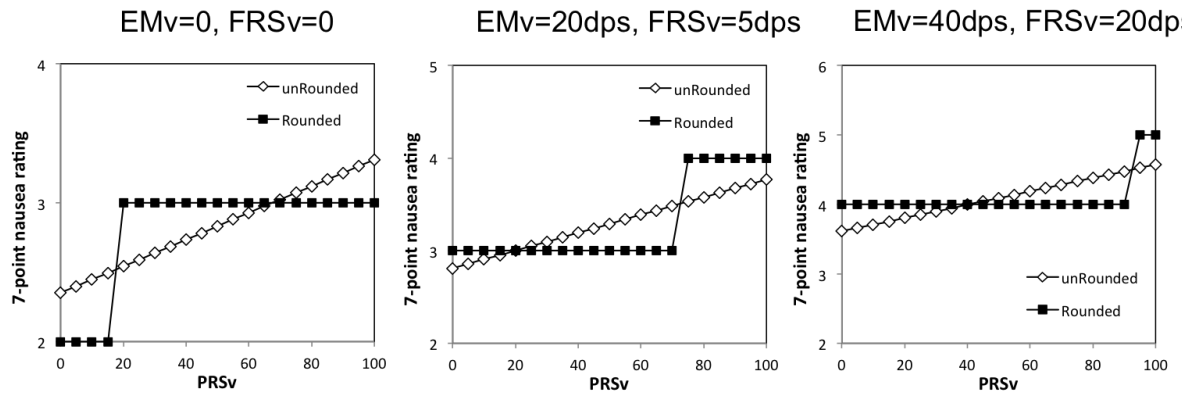


Figure 41: changes of model output on changes of peripheral retinal slip velocity. In each plot, EMv and FRSv are fixed.

Figure 41 to 43 illustrate after two factors are fixed on certain level, change in the model output to change in the 3rd factor. Define combinations of EMv, FRSv and PRSv which output VIMS higher or equal to 4 as "unsafe zone", and lower or equal to 3 as "safe zone", then they can be visualized as the cube in Figure 44. The blue area stands for the "unsafe zone" and the red area stands for the "safe zone". In daily life, not all the combinations can be achieved, but this cube illustrates under which levels of EMv, FRSv and PRSv, people could experience nausea. This plot and regression model is studied based on the average data, therefore it predicts the average VIMS people could get. For people who have high susceptibility, the panel inside the cube will move towards the origin; for people who have low susceptibility, the panel will move in the opposite to the origin.

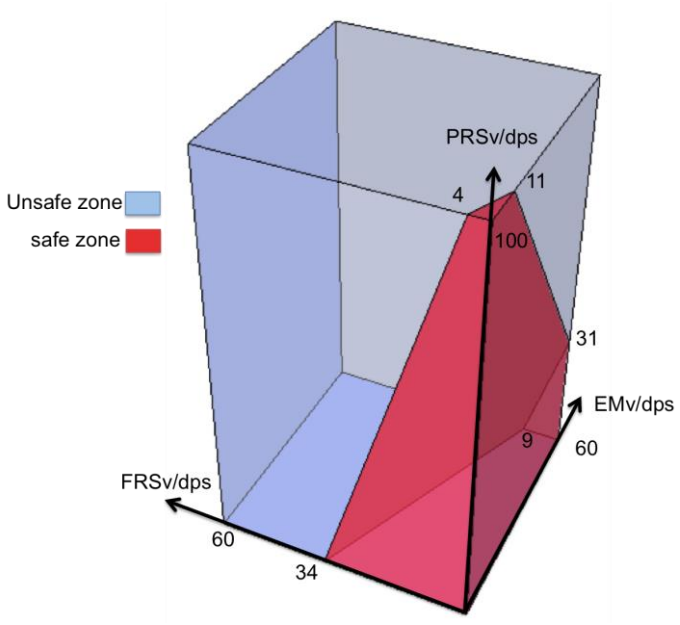


Figure 42: safe zone and unsafe zone in EMv, FRSv and PRSv cube

7.5 Application and limitations

This regression model is based on experimental data taken from male and female subjects watching a 30 minute moving black-and-white stripes of varies speed shown on a wide filed of view display (180 degrees horizontally and 90 degrees vertically) (see Chapter 3). Theoretically, the model should only be able to predict the average VIMS data under similar setting and exposure time. However, due to the generic nature of the stimuli (i.e.,patterns of an optokinetic drum), we believe this model finding can find consistency with other studies using patterns of optokinetic drum (e.g., Stern *et al.*, 1990, Hu and Stern, 1989; Duh *et al.*, 2004; Ji *et al.*, 2009; Webb and Griffin, 2001, 2003). Furthermore, while the absolute values of the nausea data will be different depending on the exposure time and stimuli used, the relative contributions of the three predictor variables: EMv, FRSv and PRSv should be generalizable.

This model, first of its kind, can open up a new way for the game industry to assess the VIMS to be provoked by a certain computer game. For example, Figure 44 can be used to visualize the combinations of EMv, FRSv and PRSv that are contributing and making a game to enter the "unsafe zone'. With the advances of camera-based EM capturing devices, capturing EMv for a particular game is very easy. Also, algorithms to extract global and regional optical flow patterns are available to determine the scene velocity from which PRSv and FRSv can be determined by adding or subtracting the EMv from the scene velocity. I admit this is only a starting point but the result has been exciting.

Chapter 8 Survival analysis of the effects of EMv, FRSv and PRSv on VIMS

8.1 Introduction to survival analysis

Survival analysis is a statistical method for analyzing data on the occurrence of events. Events may include death, injury, illness, recovery from illness or transition above or below the clinical threshold of a meaningful continuous variable (Machin, 2006). In our study, occurrence of event is defined as the first moment to report level 4 (mild nausea) in the 7-point nausea rating during a 30-minute exposure. This chapter includes mainly two parts: first, conduct survival analyses on data collected in Experiment one and two; second, conduct Cox regression to study the relative effects of eye motion, foveal retinal slip and peripheral retinal slip velocities to VIMS using the same data set collected from the five experiments used in the model described in Chapter 7.

8.1.1 Terminology

I. Probability density function of death *f(t)*

$$f(t) = \lim_{\Delta t \longrightarrow 0} \frac{P(t \le T < t + \Delta t)}{\Delta t}$$

f(t) stands for the probability of the failure time/death time occurring exactly at time t.

II. Cumulated distribution function of death *F(t)*

F(t) is the cumulated distribution function of *f(t)*. It means the proportion of number of death to the number of total sample at time *t*.

III. Survival rate *S(t)*

One goal of survival analysis is to estimate and compare survival experiences of different groups. Survival experience is described by the cumulative survival function.

$$S(t) = 1 - P(T \le t) = 1 - F(t)$$

V. Hazard function *h(t)*

Hazard function is the probability that if one survives to time *t*, he/she will die in the next instant. The deduction of *h(t)* is demonstrated as follows.

$$h(t)dt = P(t \le T < t + dt / T \square t) = \frac{P(t \le T < t + dt, T \square t)}{P(T \square t)} = \frac{P(t \le T < t + dt)}{P(T \square t)} = \frac{f(t)dt}{S(t)}$$

Therefore, the hazard function *h(t)* can be calculated by:

$$h(\mathrm{t}) = \frac{f(t)}{S(t)}, \text{ or}$$

$$h(t) = \lim_{\Delta t \longrightarrow 0} \frac{P(t \le T < t + \Delta t / T \ge t)}{\Delta t}$$

8.1.2 Cox regression

Parametric regression is used to model underlying hazard function, assuming the dependent variable (time to death or a specific event) takes on some known distribution, such as Weibull, exponential or lognormal. It then estimates parameters of these distributions using maximum likelihood estimation. Cox regression is a regression technique that models the predictors and covariates on the hazard rate, but leaves the baseline hazard rate unspecified. Cox regression model composes of two parts: first, a baseline hazard function that is left unspecified but must be positive, which can be interpreted as the hazard then all covariates are 0; second, a linear function of a set of k fixed covariates that is exponential.

$$h_i(t) = h_0(t)e^{\beta_1 x_{i1} + \ldots + \beta_k x_{ik}}, \text{ or, } \log h_i(t) = \log h_0(t) + \beta_1 x_{i1} + \ldots + \beta_k x_{ik}.$$

The $\log h_0(t)$ in the above equation can take any form. The important of Cox regression is to compare the hazard rates of individuals who have different covariates.

$$HR = \frac{h_1(t)}{h_2(t)} = \frac{h_0(t)e^{\beta x_1}}{h_0(t)e^{\beta x_2}} = e^{\beta(x_1 - x_2)}$$

Suppose there are two individuals who's $x_1 - x_2 = 1$, and they are equal in other x. (HR – 1), in which HR is given in the above formula, can be interpreted as (HR – 1) in the death rate for every one-unit increase in x.

If eye motion velocity, foveal retinal slip velocity and peripheral retinal slip velocity are treated as covariates that can predict the hazard function, their coefficients of Cox regression can be used to analyze their relative contribution to some "death event", e.g., reach level 4 in 7-point nausea rating.

8.2 Survival analysis of Experiment one

Cumulative survival rate and cumulative hazard rate of Experiment one are illustrated in Figure 43 and Figure 44. In Figure 43, it can be easily seen that cumulative survival rate in condition "EM-FRS-" (absence of EM and FRS) is higher than other conditions, and the cumulative survival rate in condition "EM+FRS+" (the presence of both EM and FRS) is lower than other conditions. Cumulative hazard rate showed in Figure 46 is consistent with Figure 45, where the condition "EM-FRS-" has the lowest hazard rate and the condition "EM+FRS+" has the highest hazard rate.

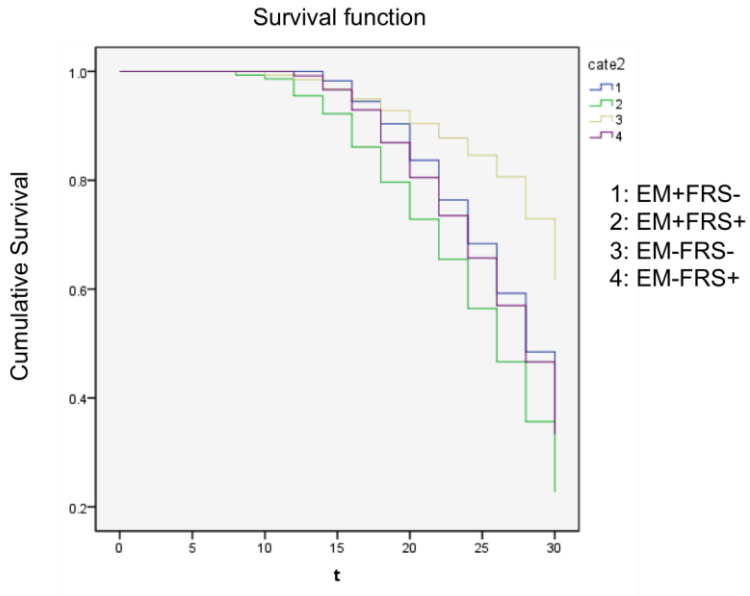


Figure 43: Cumulative survival function of four conditions in Experiment one. 1: condition A (EM+FRS-); 2, condition B (EM+FRS+); 3: condition C (EM-GRS-); 4: condition D (EM-FRS+).

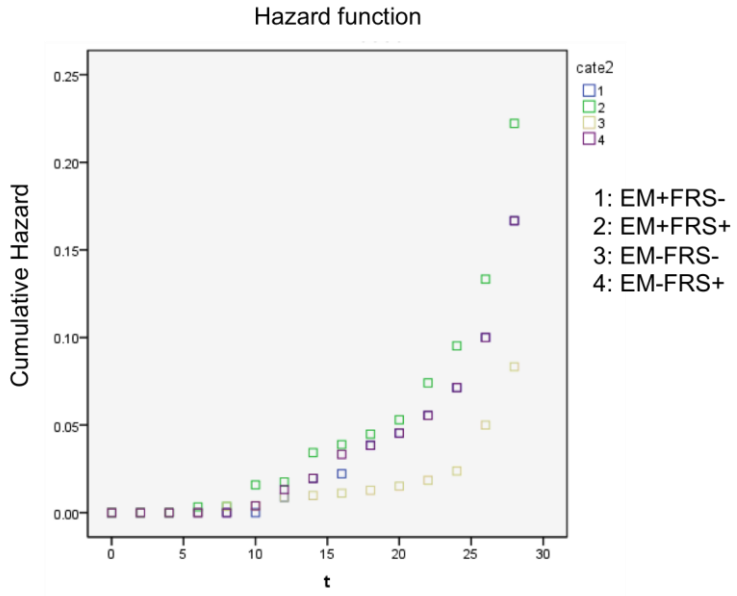


Figure 44: Cumulative hazard function for the four conditions in experiment one. 1: condition A (EM+FRS-); 2, condition B (EM+FRS+); 3: condition C (EM-FRS-); 4: condition D (EM-FRS+)

Table 17 shows the results of Wilcoxon signed ranked tests conducted to compare the number of event (reaching level 4 in 7-point nausea rating) on every pair of the four conditions in Experiment one. Number of event in condition B (EM+FRS+) is significantly higher than other conditions. Number of event in condition A (EM+FRS-) is significantly higher than condition C (EM-FRS-). Number of event in condition D (EM-FRS+) is significantly higher than condition C. This result is consistent with the statistical results reported in Chapter 4.

Table 17: Wilcoxon test on number of events in every 2 minutes in four conditions in experiment one

Condition	Condition	Wilcoxon (Gehan)	df	Sig.
A	B	7.351	1	0.007
	C	5.34	1	0.021
	D	0.407	1	0.523
B	A	7.351	1	0.007
	C	21.905	1	0
	D	4.368	1	0.037
C	A	5.34	1	0.021
	B	21.905	1	0
	D	8.181	1	0.004
D	A	0.407	1	0.523
	B	4.368	1	0.037
	C	8.181	1	0.004

Since the effect of EMv and FRSv on VIMS were significant in Experiment one, I want to know their contributions to the hazard rate, therefore Cox regression were conducted. Levels of EMv and FRSv were coded to 0 and 1. Table 18 demonstrates the regression results. Their βs in regression model $\log h_i(t) = \log h_0(t) + \beta_1 x_{i1} + ... + \beta_k x_{ik}$ are 0.473 for EMv and 0.554 for FRSv. Both are significant (p <= 0.001). Exp(β) are 1.605 for EMv and 1.740 for FRSv. These two numbers can be interpreted as: for every 40 dps increase in EMv, there will be 60.5% increase in the hazard ratio; for every 20 dps increase in FRSv, there will be 74% increase in hazard ratio. In other words, a 40 dps increase in EMv will increase the probability to reach mild nausea by 60% and a 20 dps increase of FRSv will increase the probability to reach mild nausea by 74%.

Table 18: Cox regression results of experiment one

	B	SE	Wald	df	Sig.	Exp(B)	95.0% CI of Exp(B)	
EMv	0.473	0.142	11.169	1	0.001	1.605	1.216	2.118
FRSv	0.554	0.143	15.010	1	<0.001	1.740	1.315	2.303
EMv- FRSv-						1.000		

8.3 Survival analysis of Experiment two

Cumulative survival rate and cumulative hazard rate of Experiment two are illustrated in Figure 45 and Figure 46. In Figure 45, cumulative survival rate when PRSv equals to 60 dps is slightly lower than other conditions, and there is no obvious difference among the other three conditions. In Figure 46, no obvious difference can be observed among the four conditions.

Table 19 shows the results of Wilcoxon tests conducted to compare the number of event (reaching level 4 in 7-point nausea rating) on every pair of the four conditions in Experiment four. There is no obvious difference can be observed among the four conditions. This result is also consistent with the weak statistical results reported in Chapter 5. As explained in Chapter 5, the weak effects of PRSv might have been due to the ceiling effect. In other words, the levels of nausea were already at a high level because of the presence of EMv.

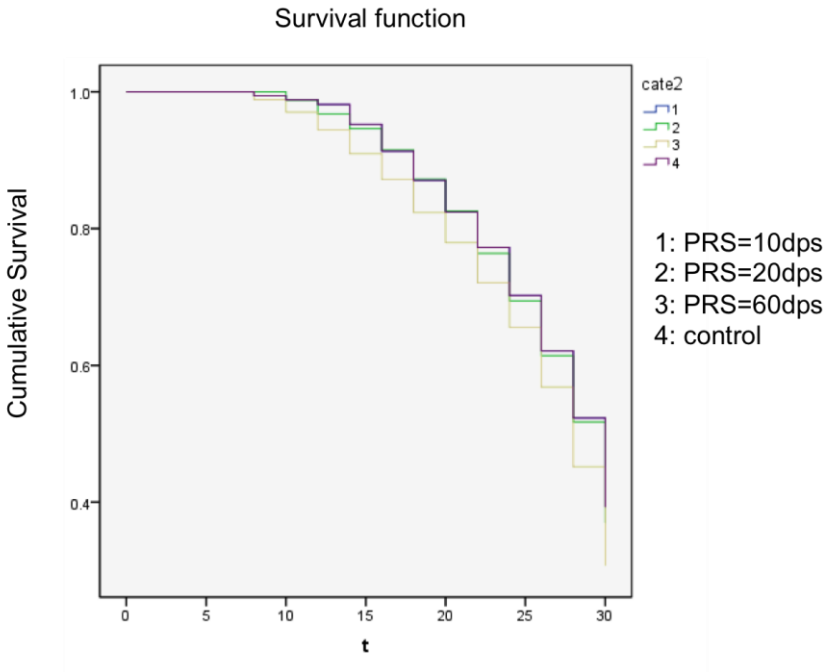


Figure 45: Cumulative survival function of four conditions in experiment two. 1: condition A; 2, condition B; 3: condition C; 4: condition D.

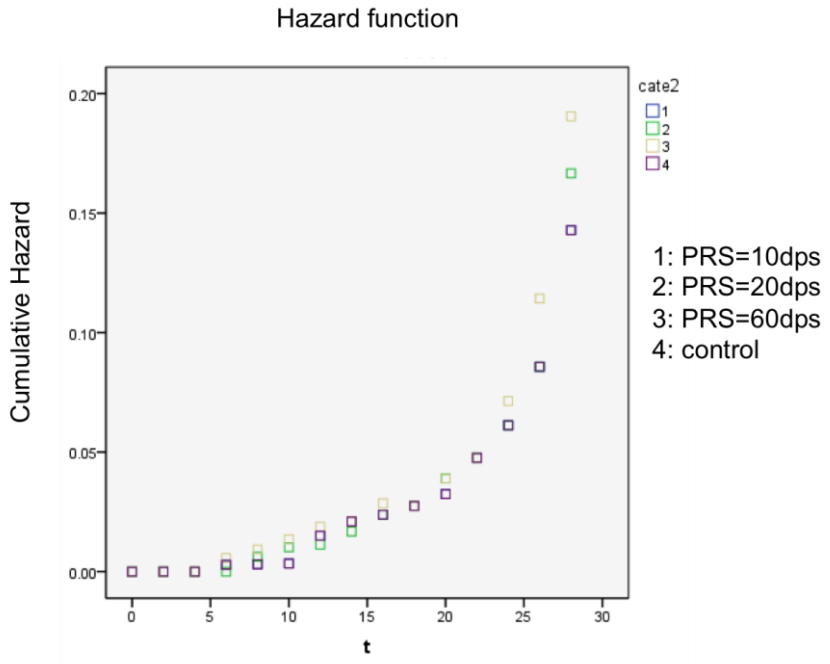


Figure 46: Cumulative survival function of four conditions in experiment two. 1: condition A (PRS=10dps); 2, condition B (PRS=20dps); 3: condition C (PRS=60dps); 4: condition D (control).

Table 19: Wilcoxon test on number of events in every 2 minutes in four conditions in experiment two

Condition	Condition	Wilcoxon (Gehan)	df	Sig.
A	B	0.027	1	0.87
	C	2.222	1	0.136
	D	0	1	1

B	A	0.027	1	0.87
	C	1.777	1	0.183
	D	0.027	1	0.87
C	A	2.222	1	0.136
	B	1.777	1	0.183
	D	2.222	1	0.136
D	A	0	1	1
	B	0.027	1	0.87
	C	2.222	1	0.136

8.4 Contributions of EMv, FRSv and PRSv to hazard rate by Cox regression

Cox regression was conducted on the same data set used in the model development in Chapter 7. Covariates to predict hazard function were set to EMv, FRSv and PRSv. Since there were more than 2 levels for PRSv and the intervals are not equal, levels of all predictors are left un-coded. Figure 47 and 48 illustrate the cumulative survival function and cumulative hazard function at mean of covariates. This means all data samples were treated to be the same, regardless of which condition it was belonged to. Table 19 lists the estimation of β in the following equation.

$$\log h_i(t) = \log h_0(t) + \beta_1 x_{i1} + ... + \beta_k x_{ik}$$

The corresponding βs of EMv, FRSv and PRSv are 0.001, 0.011 and 0.005, and exp(β) s are 1.001, 1.011 and 1.005. This can be interpreted as (i) when EMv increases by 20 dps, the hazard ratio will increase by 2%; (ii) when FRSv increases by 20 dps, the hazard will increase by 22%; and (iii) when PRSv increases by 20 dps, the hazard will increase by 10%. However, only the effects of FRSv and PRSv had been significant (p=0.043, p=0.001). The Cox regression results suggested that the effects of FRSv on nausea nearly doubled that of PRSv. Although the regression was based on more than 3000 data sample, the number of combinations of the three covariates was only 9, hence we suggest more data samples on more combinations is needed achieve a concrete conclusion.

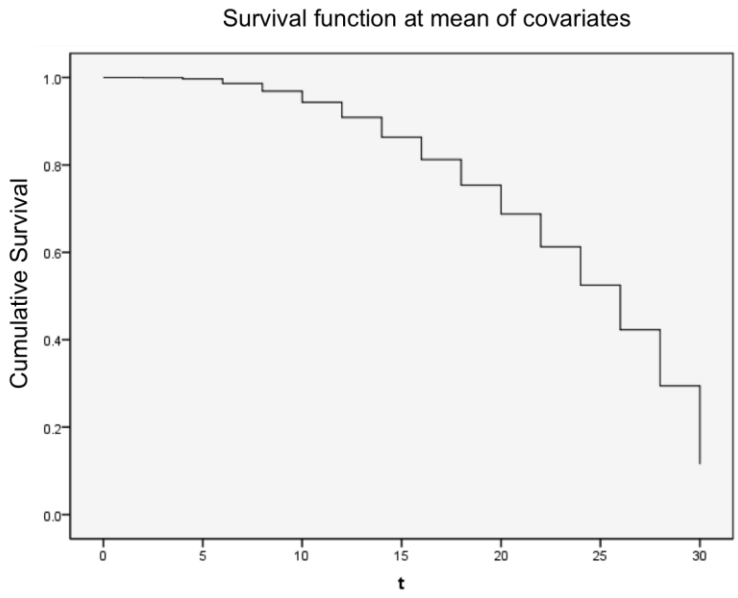


Figure 47: cumulative survival function at mean of covariates (EMv, FRSv and PRSv)

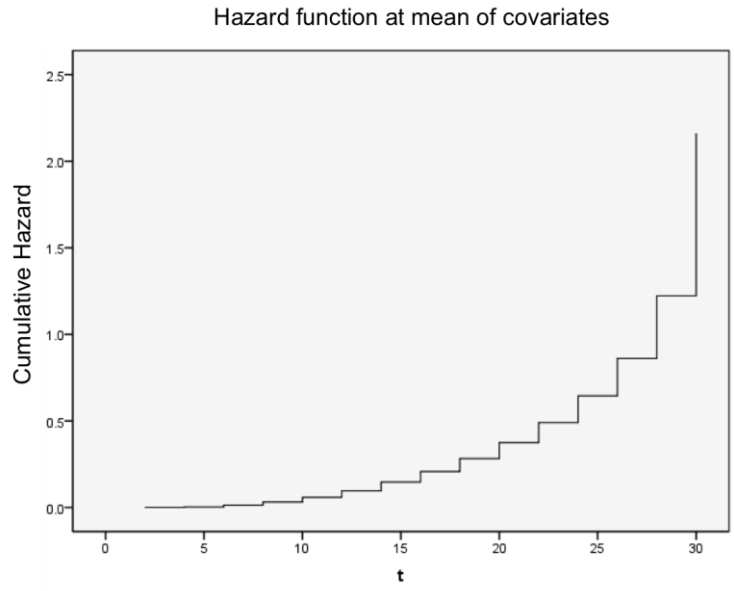


Figure 48: Cumulative hazard function at mean of covariates (EMv, FRSv and PRSv)

Table 20: coefficients estimation of Cox regression

	B	SE	Wald	df	Sig.	Exp(B)	95.0% CI of Exp(B)	
EMv	0.001	0.003	0.077	1	0.781	1.001	0.996	1.006
FRSv	0.011	0.005	4.09	1	0.043	1.011	1	1.022
PRSv	0.005	0.002	11.428	1	0.001	1.005	1.002	1.008
EMv=0 FRSv=0 PRSv=7dps						1.000		

Chapter 9 Conclusions, limitation and future work

9.1 Summary of findings

I. Findings of Experiment one: effects of eye motion velocity (EMv) and foveal retinal slip velocity (FRSv)

In the presence of EMv of around 35 dps (slow phase velocity of OKN type of EMs) and PRSv of about 15 dps, increasing FRSv from 0 to 15 dps significantly increased the rated levels of nausea (z = -2.983, p = 0.003, Wilcoxon signed rank tests) and the post SSQ total scores (z = -1.968, p = 0.049, Wilcoxon). These findings supported the FRS hypothesis that the presence of FRS alone can significantly increase levels of VIMS.

In the presence of FRSv of around 15 dps and PRSv of about 15 dps, increasing EMv from 0 dps to 35 dps significantly increased rated levels of nausea (z = -2.625, p = 0.009, Wilcoxon). This finding supported the EM hypothesis that the presence of EM alone can significantly increase levels of VIMS.

II. Findings of Experiment two: effects of peripheral retinal slip velocity (PRSv)

In the presence of EMv of 40 dps and FRSv of 20 dps, increasing PRSv from 20 dps to 60 dps significantly increased the rated levels of nausea (z = -2.133, p = 0.033, Wilcoxon).

In the presence of EMv of 40 dps and FRSv of 20 dps, increasing PRSv from 10 dps to 60 dps significantly increased the ratio scale nausea ratings (z = -2.417, p = 0.016, Wilcoxon).

Both of the above findings supported the PRS hypothesis that increases in PRSv can significantly increase levels of VIMS. For other measurements of VIMS, a trend was observed for levels of VIMS to increase when PRSv increased from 10 dps to 60 dps but the effects was not significant.

III. Findings of Experiment three: effects of active verses passive game playing and the use of an eye fixation marker

Self-rated susceptibility to motion sickness significantly correlated with the time taken to learn and achieve a pre-determined skill level of a computer game (*Pearson Corr.* = 0.53, p = 0.02).

For subjects with lower susceptibility to sickness, they reported significantly higher rated nausea levels after 30 minute passive viewing than after 30 minute active game playing (z = -2.414, p = 0.016, Wilcoxon).

The use of an eye fixation marker did not significantly reduce EMv during active game playing (p>0.05).

EMv did not vary significantly between the active game playing mode and the passive viewing mode (p > 0.05, Wilcoxon).

IV. Findings of Experiment four: effects of eye fixation and types of EM during passive viewing of a game

During passive viewing of a game, the eye fixation significantly reduced the post SSQ sub-scores of nausea (SSQN) (z = -2.388, p = 0.017, Wilcoxon).

During passive viewing of a game, about 62% of the time, the eyes fixated on a point and about 37% of the time, the eyes were performing “smooth pursuit”. The remaining 1% of the time was spent on “saccadic EM”.

V. Findings of the regression analysis:

Using data averaged across subjects watching the same visual stimuli, a regression model was constructed to study the relationship between levels of rated nausea and combinations of EMv, FRSv and PRSv:

nausea = min {Round (*0.014*EMv + 0.034*FRSv + 0.01*PRSv + 2.351*), 7}.

The R^2 was 97.4% and the adjusted R^2 was 95.0%. The p-values associated with the three predictor variables were all significant (EMv: p<0.05; FRSv: p<0.05; and PRSv: p<0.05).

VI. Findings of the Survival analysis and Cox regression:

Results of survival hazard ratio analyses of data collected in Experiment one suggested when EMv increases by 40 dps, the hazard ratio will increase significantly by 60.5%. In other

words, it would take 60.5% less time for subjects to report symptoms of 'mild nausea'. When FRSv increases by 20 dps, the hazard ratio will increase by 74%. In other words, it would take 74% less time for subjects to report 'mild nausea'.

Results of survival hazard ratio analyses also indicated that when FRSv increases by 20 dps, the hazard ratio will increase significantly by 22%. In other words, the probability to report symptoms of 'mild nausea' will increase by 22%. When PRSv increases by 20 dps, the hazard ratio will increase by 10%. In other words, The chances to report 'mild nausea' will increase by 10%.

9.2 Contributions

For the first time, eye motion velocity (EMs) and foveal retinal slip velocity (FRSv) were manipulated independently in a study on visually induced motion sickness (VIMS). Results supported the hypothesis that increasing EMv alone from 0 to 35 dps could increase levels of VIMS in the presence of constant 15 dps PRSv and 15 dps FRSv. This finding is new and it strengthens the importance of eye motion's role to VIMS (Ebenholtz *et al.*, 1994, Ji *et al.*, 2009; Stern *et al.,* 1990).

When both the EMv and PRSv were kept constant at 35 dps and 15 dps, respectively, increases of foveal retinal slip velocity (FRSv) from 0 to 15 dps alone also significantly increased the levels of VIMS. This finding is new and important because it helps to resolve the past confounding effects of EMv and FRSv. A review of literature indicated that past studies reporting reduction of VIMS by EM suppression was always confounded with FRSv suppression. In this study, these two effects have been isolated and both have been proved to have significant and similar effects on levels of VIMS. Consequently, it can be concluded that the reduction in VIMS by an eye fixation is partially due to reduction of EMv and partially due to reduction of FRSv. This finding is new and original.

Also for the first time, effects of peripheral retinal slip velocity (PRSv) was isolated and studied in the presence of controlled EMv and FRSv. Results indicated that while increasing PRSv alone in the presence of EMv (40 dps) and FRSv (20 dps) caused the levels of VIMS to increase significantly, the effects had been weak in magnitude. This suggests a possible ceiling effect because an EMv of 40 dps would have already provoked very strong VIMS.

This indicates the need to analyze the relative contribution of EMv, PRSv and FRSv on levels of VIMS – a point that will be addressed in later contribution.

Experiments three and four studied, for the first time, effects of EM on VIMS among subjects playing computer games. Results indicated that an eye fixation marker couldn't significantly reduce EMv during active playing despite instructions to subjects to look at the marker as much as possible. Not surprisingly, the use of an eye fixation marker did not reduce the levels of VIMS among the game players. This finding suggests that the previously reported laboratory findings that on VIMS reduction by an eye fixation marker could not be directly applied to game playing. Further study indicated that the use of an eye fixation marker did significantly reduce EMv as well as levels of VIMS during passive viewing of scenes from a computer game. Consequently, I believe that EMv does have a significant influence on VIMS but a simple application of an eye fixation marker is not an effective solution to control EM during game playing. Significant correlation between duration of smooth pursuit EM and levels of VIMS was found. This further verifies that EM can influence VIMS.

Having confirming that EMv, PRSv and FRSv can significantly affect levels of VIMS, a regression model has been developed to study levels of nausea and EMv, PRSv and FRSv. Results indicated that the three factors explained more than 90% variance of data collected from five experiments and each predictor variable has a significant contribution to the model output. Their relative contributions were further analyzed by survival analyses. Results indicated that an increase in EMv from 0 to 40 dps significantly increased the risk of suffering from mild nausea by 60% while an increase in FRSv from 0 to 20 dps significantly increase the risk of suffering mild nausea by 74%.

Using experimental data, combinations of EMv, FRSv and PRSv that are associated with mild nausea or more severe symptoms have been identified. Discussion on the possibility to extend this sickness contour to a method of predicting VIMS associated with a particular computer game has been presented in this thesis. This presents an opportunity for game industry to assess a game without make a player sickness.

9.3 Limitation and suggestion to future work

In Experiment two, effects of increasing PRSv from 20 dps to 60 dps in the presence of 40 dps EM has been weak. I hypothesized that the weak influence might have been due to the

ceiling effect due to the existing VIMS symptoms provoked by the 40 dps EM. A future study using wider range of PRSv (say 20 to 60 dps) and lower EMv (say 20 dps) is desirable.

Results of Experiments three and four indicated that over 60% of the time, a game player's eyes were fixating and not moving while 37% of the time the eyes were performing some form of smooth pursuit EM. Because levels of VIMS had been found to correlated with the duration of smooth pursuit EM in each exposure, future study to explore the relationship between duration of smooth pursuit EM and VIMS will be fruitful. Results can potentially be useful for game designers to design game content can will promote patterns of EMs that will provoke less symptoms of VIMS.

Although the regression model developed in Chapter 7 is successful in terms of statistical analyses of the relative contributions of EMv, FRSv and PRSv on VIMS, I admit that the way to obtain the three factors for a particular game still require some effort. Future work to automate the background recording of EMv, FRSv and PRSv during the playing of a game will be desirable. Giving the advancement of camera-based eye motion detection algorithms and optical flow algorithms, an automated solution should be technically possible.

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Appendix I: Calibration of experimental environment

1. Calibration of the center point position of the 3-projector screen:

Although the 3 screens provide the stimulus together, obviously it is the mid-screen's stimulus that is most affective to the subject. So we defined the center of the cylinder shaped by the 3-projector screen by finding a point that has almost the same distance with the two edges and the center of the mid-screen, as it is shown in the figure A.1.

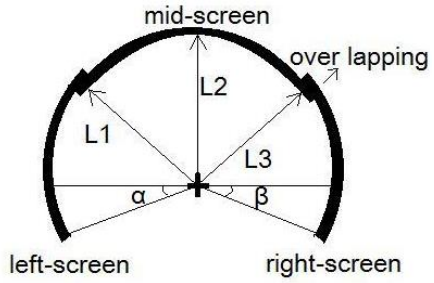

Figure A.1 An illustration of the 3-projector screen uesd in the experiment and the defination of the α and β angle. L1=116.0 cm, L2=115.6 cm and L3=117.0 cm. The "+" sign represants the center of it. The whole field of view of the 3-projector screen is 205.9°.

In the calibration, the distances were measured to be L1=116.0 cm, L2=115.6 cm, L3=117.0 cm. The maximum difference is 1.4 cm, and the mean of the radius is 116.2 cm, the error is 1.2%.

2. Calibration of the field of view of the 3-projector screen:

The field of view was measured by an angulometer. There was a straight line that passed through the center point which was just defined. The α angle was defined as the angle that how much did the left-screen exceed the line, and the β angle was defined as the angle that how much the right-screen exceed the line. The definition can also be found in the figure A.1. Each angle was measured 3 times, the data is shown in table A.1.

	1st measurement	2nd measurement	3rd measurement
α	11.5°	11.5°	11.8°
β	14.5°	13.9°	14.4°

Table A.1 The data measured for the α and β angle.

The mean of α is 11.6°, the maximum difference is 0.3°, the error is 2.6%. The mean of β is 14.3°, the maximum difference is 0.6°, the error is 4.2%. The field of view is 205.9 ° totally.

3. Calibration of the stimulus:

3.1. The field of view of a black-white striped stimulus pattern:

An angulometer was put at the center point. The angles of 3 pairs of the patterns were measured based on this point. That is, 3 black patterns and 3 white patterns. The angle was measured 3 times. They were 46.3°, 45.9° and 46°. So the mean angle for 1 pair of patterns is 15.4°. As the stimulus was designed to follow Hu et al (1989), in whose experiment the degrees for 1 pair was exactly 15°. The error is 2.4%, comparing to their research.

3.2. The velocity of the stimulus:

The velocity of the stimulus was calculated by measuring the time that a pattern would take from when it appeared at the left-screen to when it disappeared at the right-screen. The data is shown in table A.2.

condition	1st(s)	2nd(s)	3rd(s)	Mean(s)	Speed	Error(%)
6.8 dps with eye fixation	30.13	29.90	29.78	29.94	6.88	1.14
6.8 dps without eye fixation	29.97	29.88	30.03	29.96	6.87	1.06
61.5 dps with eye fixation	3.56	3.47	3.41	3.48	59.17	3.79
61.5 dps without eye fixation	3.59	3.44	3.5	3.51	58.67	4.61

Table A.2 The data measured for the velocity of the black-white striped stimulus pattern.

4. Calibration for the Polhemus tracker system:

4.1. Definition of the x, y and z axis:

The origin of the coordinate we used in the calibration was defined at the center of the transmitter. The x axis was defined as the line that was vertical to the ground and passed through the center of the transmitter. The y axis was defined as a line that was vertical to the x axis and passed through the center of the transmitter; it was also vertical to the line that passed through the center of the mid-screen and the center of the cylinder shaped by the 3

screens. The z axis was defined according to the LEFT hand rule. The definition can also be seen from the figure A.2.

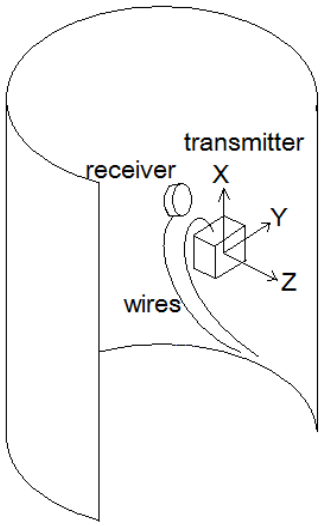

Figure A.2 Definitions of the x, y, z axis.

4.2. The range of the receiver in the calibration:

The calibration was carried out in the condition that was very similar to the experiment. As in the experiment, the receiver would be pasted at the back of the subject. The receiver would not be too far away from the transmitter. The position we set in the calibration was to keep the receiver in a hemisphere, which has the center at the transmitter and a radius of 30 cm. That is, the receiver was set in the range of 0~30 cm in the x axis direction, -30~30 cm in the y axis direction, -30~30 cm in the z axis direction.

4.3. The procedure:

The Polhemus tracker system was calibrated both in the x, y, z directions and in the azimuth, elevation, roll angles. For the x, y, z directions, the calibration was carried out by using a ruler to make it paralleled to one axis, and moving the receiver of the Polhemus tracker system along the ruler in a certain distance. Then the distance measured by the Polhemus tracker system would be then shown on the computer. For the azimuth, elevation, roll angles, an angulometer was used to make sure that the receiver had been rotated in a certain angle. Then the angles shown by the Polhemus tracker system would be compared with that certain angle. Each calibration was measured 6 times, with 3 times in the positive direction and 3 times in the negative direction.

The distance set for the x, y, z directions was 10 cm, and the angle for the azimuth, elevation and roll was 30 degrees. If the subject moved a larger distance than 10 cm or rotated a larger angle than 30 degrees, the experimenter could be able to observe such movement clearly, so any larger distance or angle were not calibrated.

4.4. The results:

4.4.1. Calibration in x direction:

	X(cm)	Y(cm)	Z(cm)	x (relative)	y (relative)	z (relative)	Azimuth (°)	Elevation (°)	Roll (°)
1	5.42	-1.11	-23.52				-178.99	0.62	3.85
	15.57	-0.93	-23.40	10.15	0.18	0.12	-179.99	1.18	3.76
2	5.45	-1.12	-23.53				177.27	1.04	2.65
	15.63	-1.29	-23.30	10.18	-0.16	0.22	177.93	1.35	1.32
3	5.35	-1.07	-22.89				-179.05	3.77	3.82
	15.43	-0.87	-21.77	10.08	0.21	1.13	177.11	5.25	1.84
4	29.66	-2.63	-21.68				179.17	0.34	1.43
	19.58	-2.66	-21.70	-10.08	-0.02	-0.02	176.19	0.06	-3.97
5	29.53	-3.78	-18.96				174.04	2.64	-5.20
	19.43	-3.70	-19.75	-10.10	0.08	-0.79	175.87	2.63	-8.32
6	29.61	-6.01	-20.61				174.26	-0.67	-6.17
	19.53	-5.86	-19.94	-10.08	0.15	0.67	176.95	-3.93	-5.91

Table A.3 the data measured for the calibration of X direction.

The mean of the 6 measurements was 10.11 cm, and the error here is 1.1%.

4.4.2. Calibration in y direction:

	X(cm)	Y(cm)	Z(cm)	x (relative)	y (relative)	z (relative)	Azimuth (°)	Elevation (°)	Roll (°)
1	2.44	3.63	24.42				139.17	5.09	6.15
	2.20	-6.28	24.66	-0.24	-9.91	0.24	141.59	-6.25	6.38
2	2.66	4.91	24.43				136.66	-5.13	5.68
	2.26	-4.99	24.65	-0.40	-9.90	0.22	141.42	-5.97	6.25
3	2.70	5.02	24.26				139.18	-4.90	4.62
	2.31	-4.87	24.38	-0.38	-9.89	0.12	140.75	-3.81	4.89
4	3.00	9.61	24.47				-143.71	-5.74	-5.70
	3.01	19.49	24.39	0.01	9.88	0.08	-143.63	-3.26	-3.86
5	2.94	10.79	24.34				-144.05	-4.39	-4.93
	3.00	20.76	24.34	0.05	9.98	0.00	-144.70	-3.34	-3.53
6	3.11	10.73	24.18				-144.06	-3.83	-4.19
	3.06	20.73	24.20	-0.04	10.00	0.01	-144.34	-2.38	-2.77

Table A.4 the data measured for the calibration of Y direction.

The mean of the 6 measurements was 9.92 cm, and the error here is 0.7%.

4.4.3. Calibration in z direction:

	X(cm)	Y(cm)	Z(cm)	x (relative)	y (relative)	z (relative)	Azimuth (°)	Elevation (°)	Roll (°)
1	2.79	9.16	12.42				-175.11	-3.51	-1.22
	4.46	9.04	22.30	1.66	-0.12	9.88	174.80	-5.98	1.77
2	2.14	9.39	12.14				-172.96	-2.62	0.59
	4.51	9.04	21.99	2.36	-0.35	9.85	-176.06	-8.94	-1.04
3	1.48	10.21	12.45				-170.89	-2.60	-0.98
	2.83	10.17	22.17	1.35	-0.05	9.72	-177.56	-3.79	3.23
4	10.25	-8.89	-8.76				179.98	-0.35	-1.24
	9.31	-8.64	-19.06	-0.95	0.25	-10.31	176.36	-5.37	3.45
5	10.17	-8.85	-9.10				179.68	0.87	3.25
	9.31	-8.72	-19.29	-0.86	0.13	-10.18	174.69	-9.28	-0.59
6	10.30	-8.73	-8.85				-175.27	-0.09	0.02
	9.43	-8.61	-19.10	-0.87	0.12	-10.25	-179.60	-5.88	-2.13

Table A.5 the data measured for the calibration of Z direction.

The mean of the 6 measurements was 10.03 cm, and the error here is 0.3%.

4.4.4. Calibration in azimuth angle:

	X(cm)	Y(cm)	Z(cm)	Azimuth (°)	Elevation (°)	Roll (°)
1	7.75	-10.47	-22.65	29.56	-1.61	1.07
2	7.75	-10.44	-22.55	29.90	-1.72	1.37
3	7.76	-10.45	-22.55	29.51	-1.75	1.22
4	7.42	-2.23	-22.76	-29.44	0.08	-3.30
5	7.51	-4.85	-22.73	-28.99	0.13	-2.72
6	7.53	-4.76	-22.71	-29.31	0.15	-2.64

Table A.6 the data measured for the calibration of the Azimuth angle.

The mean of the 6 measurements was 29.45 degrees, and the error here is 1.8%.

4.4.5. Calibration in elevation angle:

	X(cm)	Y(cm)	Z(cm)	Azimuth (°)	Elevation (°)	Roll (°)
1	8.86	-6.84	-21.96	7.13	-29.69	-7.84
2	8.65	-6.33	-21.78	6.50	-29.43	-3.07
3	9.43	-6.50	-22.83	-4.51	-29.90	-1.12
4	1.24	-27.15	-8.82	-1.55	29.70	5.59
5	1.29	-26.92	-9.38	-1.02	31.33	1.00
6	1.13	-27.36	-8.77	-4.19	29.89	-0.35

Table A.7 the data measured for the calibration of the Elevation angle.

The mean of the 3 measurements was 29.67 degrees, and the error here is 1.1%.

4.4.6. Calibration in roll angle:

	X(cm)	Y(cm)	Z(cm)	Azimuth (°)	Elevation (°)	Roll (°)
1	12.90	-4.42	-21.90	3.58	-2.46	30.27
2	12.79	-4.64	-22.08	-1.64	0.79	29.22
3	13.42	-3.76	-21.52	3.33	-2.16	29.97
4	12.04	-11.82	-22.41	-1.53	1.89	-29.92
5	12.01	-11.44	-22.43	0.96	6.63	-28.89
6	12.06	-11.79	-22.37	-0.89	2.45	-29.09

The mean of the 6 measurements was 29.56 degrees, and the error here is 1.5%.

Table A.8 the data measured for the calibration of the Roll angle.

4.5. Conclusions:

The error of all the directions of the Polhemus tracker system was less than 2%.

Appendix II: Instruction of experiment one and two

1) The objective of this experiment is to study your response to moving image.
2) Please keep your eyes open during the whole experiment except experimenter asks you to close your eyes (you can have normal blinking).
3) Please maintain your head position on the chin rest (don't move your head) during the whole experiment. Please hold the chin rest with both hands. Press your chin and fore head against the chin rest at all time.
4) During the experiment, we will put on 5 EOG electrodes. Please try not to move touch EOG electrode and their connecting wire during the experiment.
5) During the experiment, you will be asked to rate your various responses to this visual stimuli using 3 different methods. Please read the following instructions for each methods carefully and make sure you have fully understanding on all of them:

A. Measurement 1 (M1): rate your strength level of perceived nausea using a number (Now, please tell the experimenter what is the meaning of "nausea" in your native language)

Instruction of M1:

During the experiment you, you will watch an image pattern rotating at constant velocity for 30 mins. Your task is to tell me how much your sensation of nausea is induced and how the strength of nausea changes within the 30mins by assigning numbers. When you are asked to open your eyes and view the rotating pattern or the eye fixation point if there is one, give a number to represent the current nausea severity level you perceive.
***Notes**: At the moment when you open your eye, If you have no sensation of nausea, just give a non-zero number (e.s., 10, 100, or any other number).*
After that, at 2 mins interval during the experimentl, I will ask you to give your current nausea severity level a number. Let high numbers represent high nausea level and low numbers represent low nausea level. Try to make the ratios between the numbers that you assign correspond to the ratio between the nausea levels you felt at different time. In other words, double your reported non-zero number when you felt your nausea level is doubled and halve your reported non-zero number when you felt your nausea level is half reduced, and so on. Remember that you can assign any number. There is no limit to the number that you may assign. There is no right or wrong answer. I just want to know how you judge your perceived nausea level over time. When I ask you to assign a number to your current level of nausea, I will remind you about your last assigned number 2 min ago. Any question?

B. Measurement 2 (M2): rate your strength level of perceived nausea by scale A to G.
Instruction of M2:
During the experiment you will watch an image pattern rotating at constant velocity for 30 mins. Your task is to tell me how much nausea is induced and how its strength changes within the 30mins by assigning A-G according to the following scale:

Rating	Definition
A	No symptoms
B	Any unpleasant symptoms, however slight

C	Mild unpleasant symptoms, e.g. stomach awareness, sweating but no nausea
D	Mild nausea
E	Mild to moderate nausea
F	Moderate nausea but can continue
G	Moderate nausea, want to stop

In summary, when you are asked to open your eyes and view the rotating pattern, give your current nausea severity rating based on the above scale. During the experiment, at 2 mins interval, I will ask you to give your current rating from time to time. Any question?

C. Measurement 3 (M3): rate your perceived vection (self-motion) continuously on a percentage scale:

You report	Perception of motion (vection)
0	You feel like you are stationary and it is the image which appears to be moving only.
1-49%	You feel like you are moving a bit, but the image is moving more.
50%	You feel like you are moving at the same speed as the image.
51-99%	You feel like you are moving a lot and the image is moving a bit.
100%	You feel like you are moving and the image appears stationary.

Remember the line length estimation tests that you have completed. In the line length estimation test, the numbers that you reported were proportional to your estimation line length. In the above vection scale, the % that you will report should also be proportional to the relative speed between yourself and the visual pattern. In particular, 0% means that you feel like you are stationary and it is the pattern that appears to be moving. 100% means that you feel like you are moving and the pattern appear stationary. 50% means that you feel like you are moving at the same speed as the pattern.
During the experiment, at 2 mins interval, I will ask you to give your current rating from time to time. Any question?

Appendix III: Pre-exposure and Post-exposure Simulator Sickness Questionnaires (Kennedy, 1993)

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

一般不適	1. General discomfort	None	Slight	Moderate	Severe
疲倦	2. Fatigue	None	Slight	Moderate	Severe
沉悶	3. Boredom	None	Slight	Moderate	Severe
想睡	4. Drowsiness	None	Slight	Moderate	Severe
頭痛	5. Headache	None	Slight	Moderate	Severe
眼痛	6. Eyestrain	None	Slight	Moderate	Severe
很難集中視力	7. Difficulty focusing	None	Slight	Moderate	Severe
口水分秘增加	8. Salivation increase	None	Slight	Moderate	Severe
口水分秘減少	Salivation decrease	None	Slight	Moderate	Severe
出汗	9. Sweating	None	Slight	Moderate	Severe
作嘔	10. Nausea	None	Slight	Moderate	Severe
很難集中精神	11. Difficulty concentrating	None	Slight	Moderate	Severe
精神的壓抑	12. Mental depression	No	Yes (Slight	Moderate	Severe)
頭脹	13. "Fullness of the head"	No	Yes (Slight	Moderate	Severe)
視野模糊	14. Blurred vision	No	Yes (Slight	Moderate	Severe)
眼花 (開)	15. Dizziness eyes open	No	Yes (Slight	Moderate	Severe)
眼花 (合)	Dizziness eyes close	No	Yes (Slight	Moderate	Severe)
眩暈	16. Vertigo	No	Yes (Slight	Moderate	Severe)
幻覺	17. Visual flashbacks*	No	Yes (Slight	Moderate	Severe)
昏厥	18. Faintness	No	Yes (Slight	Moderate	Severe)
呼吸異樣	19. Aware of breathing	No	Yes (Slight	Moderate	Severe)
胃感覺異樣	20. Stomach awareness	No	Yes (Slight	Moderate	Severe)
沒有胃口	21. Loss of appetite	No	Yes (Slight	Moderate	Severe)
胃口增加	22. Increased appetite	No	Yes (Slight	Moderate	Severe)
想去洗手間	23. Desire to move bowels	No	Yes (Slight	Moderate	Severe)
迷惘	24. Confusion	No	Yes (Slight	Moderate	Severe)
打嗝	25. Burping	No	Yes (Slight	Moderate	Severe)
嘔吐	26. Vomiting	No	Yes (Slight	Moderate	Severe)
其他	27. Other	No	Yes (Slight	Moderate	Severe)

SYMPTOM CHECKLIST (Post-exposure)

confidential

Post-exposure instruction: please fill in this questionnaire once more. Circle below if any of the symptoms apply to you now.

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 IV: Calculation of SSQ total scores and three sub-scores (Kennedy, 1993)

None = 0

Slight = 1

Moderate = 2

Severe = 3

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

Score

Nausea = [1] × 9.54

Oculomotor = [2] × 7.58

Disorientation = [3] × 13.92

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

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* Total is the sum obtained by adding the symptoms scores. Omitted scores are zero