Effects of Navigation Velocities in Fore-and-aft, Lateral, Yaw Axes on Cybersickness Caused by Exposure to A Virtual Environment

by

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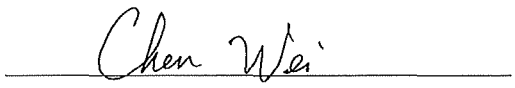

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This is to certify that I have examined the above MPhil thesis
and have found that it is complete and satisfactory in all respects,
and that any and all revisions required by
the thesis examination committee have been made.

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TABLE OF CONTENTS

List of Figures

List of Tables

Effects of Navigation Velocities in Fore-and-aft, Lateral, Yaw Axes on Cybersickness Caused by Exposure to A Virtual Environment

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Abstract

Viewers exposue to a Virtual Environment (VE) can exhibit symptoms of motion sickness, such as eyestrain and nausea. This type of motion sickness has been referred to as cybersickness and is a major ergonomics concern with the use of VEs (Stanney et al., 1998).

Literatures show that visual scene movement perceived during navigation in a VE plays an important role in producing cybersickness. In particular, previous studies have shown that speed of navigation through a VE can significantly affect the levels of cybersickness. The purpose of this research is to study the effects of navigation velocities in different axes on the levels of cybersickness. Due to limitations in resources, the effects of navigation velocities have been studied in only three axes of navigation.

Experiment 1 studied the effects of navigating through a VE in different translational axes (i.e., fore-and-aft, lateral, vertical) on cybersickness. Results indicated that navigations in all three translational axes could significantly increase the level of cybersickness as measured by nausea ratings and Simulator Sickness Questionnaire (SSQ) scores ($p<0.01$). In addition, participants reported significantly lower sickness level with navigation conditions in the fore-and-aft axis ($p<0.05$) and navigating in lateral or vertical axes in the same VE resulted in similar levels of cybersickness.

Later experiments would focus on the effects of navigation velocities in the fore-and-aft axis and lateral axis.

Experiment 2 studied the effects of navigation velocities ranged from 3m/s r.m.s. to 150 m/s r.m.s. in fore-and-aft axis on level of cybersickness. Experiment 3 studied the effects of navigation velocities in lateral. In both experiments, a significant main effect of velocities on levels of cybersickness was found ($p<0.01$) and a nonlinear relationship between navigation velocities in fore-and-aft or lateral axis and levels of cybersickness was identified.

Since a previous study has shown that exposures to an oscillating VE in different rotating axes result in similar levels of cybersickness, this research studies the effects of navigation velocties in only one rotational axis: the yaw axis. Experiment 4 studied the effects of navigation velocities in yaw axis on levels of cybersickness. A significant main effect of navigation velocities on cybersickness was found ($p<0.01$) and a nonlinear relationship between navigation velocities in yaw axis and levels of cybersickness was identified.

The experimental findings are compared with the past literature concerning visually induced motion sickness with rotating drums. In particular, the consistency among the findings was discussed.

Chapter 1: Introduction

1.1 Significance of cybersickness associated with VR simulations

Virtual Reality (VR) systems represent a revolutionary development in human-computer interaction techniques that allow users to step into Virtual Environment (VE) generated by a computer. The term 'Virtual Reality' was initially coined by Jaron Lanier, *"the leading innovator of virtual reality software"* (quoted from Williams, 2002), in 1989. With the application of different VR technologies, e.g., head-mounted display (HMD), data gloves, and joysticks etc, users are brought to different real or even imaginative world situations that are completely generated by a computer. With the advancements in computation power of computers recently, more realistic, complicated or even unbelievable VEs are now being developed. The amazing movie series The Matrix, written and directed by Andy and Larry Wachowski, have elevated the VE as well as the relationship between human and machine to the highest achievement, although this occurred only on the screen at the moment (http://whatisthematrix.warnerbros.com).

Virtual Environment applications have emerged in military, training, entertainment, education, medical and other areas. Pilot training VEs contribute a lot to the aerospace engineering community. Turning now to space exploration, the use of VEs in space community is also amazing. For example, the use of digital panoramic techniques helps scientist 'explore' the landing site of the *Mar's pathfinder,* (http://mars.jpl.nasa.gov/default.html). On-line education could also be implemented by VR technology. 'Virtual teacher' and 'virtual student' could be developed to simulate

the education process (for example, http://www.skally.net/eduvr/). 3D objects, scenery and live scenario can give learners a clearer picture of their topic as well as better understanding. This makes the learning process more interactive and effective. In medicine and surgery areas, VR techniques can be applied in the fields covering surgical intervention and planning, medical therapy, medical training and skill enhancement and more (Westwood, 1998). The promise of the technology is to provide better surgical results with fewer procedures, decreased time in the operating room, lower risk to the patient (increased precision of technique, decreased infection risk), and a lower resulting cost. Definitely, with the development of VR technologies, more and more VEs will be developed and they will permeate our life. However, everything has two sides. Despite the attractiveness of amazing interactions generated by this innovative technology, there are also a number of different health and safety concerns while users are exposed to the VR simulations. These concerns may limit VR technologies ultimate usability and threat to reduce the impact of VR in our culture, society, and the workplace. Health and safety issues related to VR simulation cover eye strain, repetitive strain injury, neck strain, etc. Above all, the one over-riding health and safety issue is cybersickness – one type of motion sickness associated with the use of VEs (Viirre and Bush, 2002).

Some users exhibit motion sickness symptoms during or after VR simulation exposure. The typical symptoms include nausea, dizziness, and drowsiness. This type of motion sickness occurred in VEs is called cybersickness, which is coined by McCauley and Sharkey in 1992. Due to the natural characteristics of VR simulation, cybersickness is usually treated as visually-induced motion sickness (Hettinger et al., 1992; McCauley

and Sharkey, 1992; Kennedy et al., 1993) since the main stimuli is caused by visual information in VEs.

Such negative after-effects of VR simulation exposure will affect safety and health, user acceptance, and user performance. Problems of disorientation and nausea in VR have been ascribed to temporal and spatial distortion between actual motions of the user's body and corresponding movements of displayed images (McCauley and Sharkey, 1992). Such distortions have also been shown to "*degrade the performance of tracking, manipulation and reading task*" (quoted from Lewis and Griffin, 1997). Stanney et al. (1998) represented a committee summary of the state of knowledge regarding human factors issues in VEs. Stanney et al. proposed that identifying the aftereffects of exposure to VR simulation was the most important issues related to human factors research in VEs. Therefore, Researches on cybersickness contribute to critical importance for human health and safety issues. Obviously, cybersickness is the most significant problem which will affect the development of VR technology.

1.2 Visual scene movements play an important role in generating cybersickness

Much research has been done focus on cybersickness. Unfortunately, the underlying mechanism and consequences of cybersickness are still not clearly understood yet. However, in particular, the review of literature (Hettinger and Riccio, 1992; Kennedy et al., 1996; McCauley and Sharkey, 1992; Hu et al., 1997) show visual stimuli describing the movements of visual scene inside VEs can play a very important role in producing cybersickness. Navigation inside VEs is an essential causal factor to cybersickness.

Hence, in some sense, cybersickness is also believed as a type of visually induced motion sickness. Current VE systems can often provide scenarios such as a user can be physically stationary but yet has a compelling sense of self-motion navigating in VEs through watching moving images. Illusory self-motion, named vection, within a VE will make users have the feeling to be personally on the scene, but for many users it will result in cybersickness.

Why can visual scene movements cause cybersickness? Human beings rely on vision system and vestibular system when interpreting motions. Under ordinary circumstances, there is a direct correspondence between sensory information from visual and vestibular system and its associated neural store based on past experience. According to sensory rearrangement theory (Reason, 1978), under the scenarios described in the previous paragraph, visual sensor indicates movement while vestibular sensor indicates stationary, hence a sensory mismatch among visual inputs and vestibular inputs occur; and this multiple sensory integration may not agree with human's existing experience stored in the brain, then motion sickness symptom may be produced. The response to VE exposure varies directly with the dose (i.e., VE stimulus intensity), capacity of the individual exposed (e.g., susceptibility, experience), and exposure duration etc.

In a typical VR simulation, the main stimuli come from visual information. As cybersickness is believed to be a type of visually induced motion sickness, studying the relationship between visual stimuli experienced by users of VR simulation and the level of cybersickness should contribute important knowledge to the research field of cybersickness.

1.3 Purpose of this study

Given the consequences of cybersickness, there would be significant benefit to study the relationship between scene movements in VE and the level of cybersickness. Previous study utilizes Spatial Velocity (So et al., 2001a) which consists of two components, i.e., Scene Complexity and Navigation Velocity in different navigation axes to quantify the scene movements in VEs. After reviewing the literature, although a wide body of literature exists on motion sickness in Virtual Environments, we found the research gaps among the current existing studies. The existing studies concerning effects of navigation velocities on cybersickness in VR simulations is limited to fore-and-aft axis. Since navigation in VR simulation can possibly occur in six axes, i.e., three rotational axes and three translational axes, several questions are still waiting to be answered, i.e., what are the effects of visual scene movements in the other axes besides fore-and-aft axis. Will visual scene movements in other motion axes have the same effects on cybersickness as we found in fore-and-aft axis? Furthermore, what are the differences between the effects of scene movements in different axes?

In order to explore the relationship between scene movements in VEs, especially, we focus the factor of navigation velocity, and the rated level of cybersickness, firstly, we need to compare the navigation in translational axes in VEs so that can this study can complement a previous peer study (Lo and So, 2001) which investigated the effects of rotational scene oscillation in VEs; Moreover, the different levels of navigation velocities in different axes should be manipulated and further studied. Due to

limitations in resources, the effects of navigation velocities have been studied in only three axes of navigation.

The specific objectives of this study are as described below:

1. To study the effects of navigations in different translational axes on the level of cybersickness.
2. To study the effects of different levels of navigation velocities in fore-and-aft on the level of cybersickness
    a. Using another virtual environment to compare with the results from previous studies;
    b. Extend the range of navigation velocity to study the extremity
3. To study the effects of different levels of navigation velocities in lateral on the level of cybersickness.
4. To study the effects of different levels of navigation velocities in yaw on the level of cybersickness.

This study can provide the VR designer the referencing information on design specifications and strategies for users to keep the balance between the feeling of presence and motion sickness. This is especially important for design of VR consumer products, use of VR for command and control, and for training process.

1.4 The organization of the thesis

The outline of the thesis is illustrated in Figure 1.1.

Chapter 1 explains the background information associated the problems of cybersickness in VEs and states that visual scene movement plays an important role in producing cybersickness.

Chapter 2 is the literature review chapter. It reviews the literature on characteristics and major theories on cybersickness, as well as the relationship between visual scene movement and cybersickness. In particular, previous studies on effects of different level of navigation velocities as well as effects of different navigation axes on level of cybersickness are reviewed.

Chapter 3 presents the experimental work on investigating the effects of scene movements in three different axes (i.e., fore-and-aft, lateral and vertical) on the level of cybersickness in VEs.

Chapter 4 presents the experimental work on investigating the effects of different level of navigation velocities in fore-and-aft on level of cybersickness. This work is a repeated and extension experiment compared with a previous study.

Chapter 5 presents the experimental work on investigating effects of different level of navigation velocities in lateral on level of cybersickness.

Chapter 6 presents the experimental work on investigating effects of different level of navigation velocities in yaw on level of cybersickness.

Chapter 7 presents the overall discussion, and general conclusion of the four experimental works.

Chapter 8 states the limitations and some suggestions on the future work.

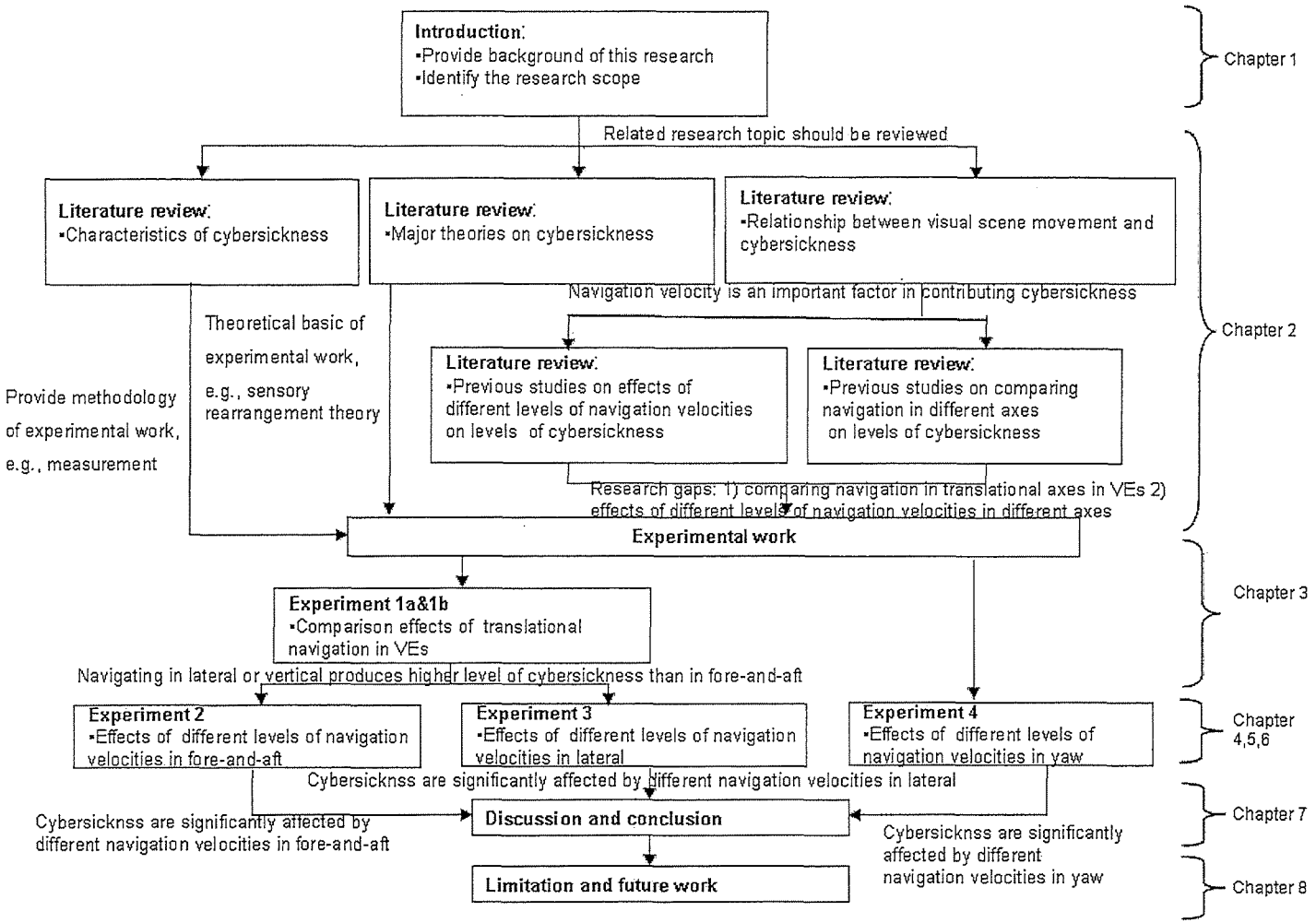

Figure 1.1 Outline of the thesis

Chapter 2: Literature Review

2.1 Characteristics of cybersickness

2.1.1 Definition and symptoms

Most people are familiar with motion sickness. When traveling across sea or sitting on a car, a passenger may feel uncomfortable and develop adverse symptoms, with typical signs include drowsiness, dizziness, sweating, nausea and even vomiting. Cybersickness is a type of motion sickness associated with Virtual Reality simulation.

Researches have shown that approximately 80% to 95% of those exposed to a VE report some level of symptomatology post exposure. Stanney et al. (2002) summarized that VE exposure can cause people to vomit (about 1%), experience nausea (about 69.9%), disorientation (about 67.5%), and oculomotor problems (about 77.7%). It can also cause sleepiness (about 41.9%) and visual flashbacks (about 11%).

Cybersickness is a significant problem influencing the development of VR technology. Cybersickness can result in nausea, headaches, dizziness (in as many as 80~95% of VE users will suffer from these symptoms); compromised safety due to visual flashbacks and postural disturbances (for example, in driving); compromised training achievement; lack of confidence in the VE leading to decreased use. It is critical to investigate the problem of cybersickness.

2.1.2 Measurements

In order to study cybersickness, it is important to quantify the level of cybersickness experienced by the users after VR simulation exposure. However, McCauley and Sharkey (1992) pointed out that the measurement of cybersickness is challenging because of the variety of the sickness symptoms as well as the characteristics of the internal symptomatology associated. Systematic methods of measuring cybersickness are needed. The most common form of measurement is subjective self-report of symptomatology during or after exposure. Meanwhile, objective measurements are also developed during these years.

2.1.2.1 Subjective measurements

Nausea is a common symptom across different types of motion sickness such as carsickness and seasickness. Obviously, it is also a usual and representative symptom associated with cybersickness. Golding and Kerguelen (1992) proposed a 7-point nausea rating in assessing the level of motion sickness experienced by participants in their experiments (Appendix A). This scale has been adopted in various motion sickness related research (Griffin and Woodman, 1997; Lo et al., 2001; So et al., 2001b).

The Simulator Sickness Questionnaire (SSQ) (Kennedy and Lane, 1993) is the most commonly used tool to assess subjective symptomatology from VE exposure. The SSQ consists of a checklist of 26 symptoms (See Appendix B), each of which is designated in terms of degree of severity (0: none; 1: slight; 2: moderate; 3: severe). Those multi-

symptom questionnaire measuring items include from general discomfort and fatigue to specific symptoms such as increased salivation, sweating, headache, eyestrain, dizziness, vertigo, etc. A weighted scoring procedure is used to obtain a global index, known as the Total Severity (TS) score, which reflects the overall total discomfort level, as well as scores along three subscales (i.e., nausea, oculomotor, disorientation). By means of these subscales, cybersickness can be more fully characterized.

2.1.2.2 Objective measurements

Although using SSQ or nausea rating scale is a simple and easy way to evaluate the sickness level during or after exposure of VR simulation, it is possible that different individual has different subjective feeling in explaining the level of sickness. Recent results from VE studies indicate that it would be beneficial to supplement these subjective reports with standardized and normalized objective measures of aftereffects (Stanney et al., 1998). Objective measures of sickness level from VE exposure include postural stability test, changes in ElectroEncephaloGram (EEG), eye movements' measurement as well as heart rate levels and variability etc. Among these measurements, postural stability test is the most common method as reported in lots of literature (Hamilton et al., 1989; Kennedy et al., 1993; Cobb, 1999).

Postural stability is the ability of an individual to maintain balance and postural control. It is hypothesized that the severity of motion sickness will be scaleable directly to the duration and magnitude of postural instability experienced (Hamilton et al., 1989; Kennedy et al., 1993; Cobb, 1999). Postural stability is usually measured using two

types of floor-based tests. One is called static posture test --- measured in terms of how long a person can hold a static posture; and the other is called dynamic posture test --- such as performing a walking task with equipments. In our experiments, only static posture tests were adopted due to the limited resources. Static postural tests require the participants to keep a specific posture and try their best to balance themselves for a period of time. Three static postural tests adopted in our experiments as described below:

Sharpened Romberg (SR): subjects are asked to stand heel-to-toe on the floor with their weight equally distributed on both feet, chin parallel to floor and arms folded against their chest and eyes closed. This posture is maintained for 60 seconds or until the subject's foozt moved or balance is lost (Cobb, 1999; Hamilton et al., 1989; Kennedy et al., 1993).

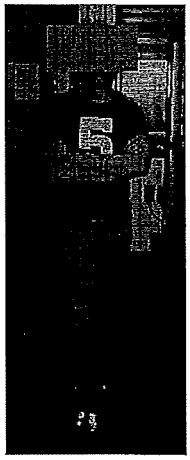

Figure 2.1 Illustration of Sharpened Romberg posture

Standing on preferred leg (SOPL): this test is identical to the SR except that subjects are asked to stand on one preferred leg with the other leg bent at the knee and extended behind so that the thighs are touching. This stance is maintained for a maximum of 30 seconds or until the subject's foot moved or balance is lost (Hamilton et al., 1989; Kennedy et al., 1993).

Standing on none-preferred leg (SONL): this test is identical to the SOPL except that subjects are asked to stand on none-preferred leg. This stance is maintained for a maximum of 30 seconds or until the subject's foot moved or balance is lost (Hamilton et al., 1989; Kennedy et al., 1993).

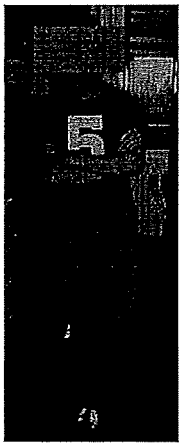

Figure 2.2 Illustration of Stand On one leg eye closed posture

Besides postural stability, changes in EEG which is a test to detect abnormalities in the electrical activity of the brain, and frequencies of eye movements measured by ElectroOculoGraphy (EOG) have been proved to be good indicators of sickness severity (Hu et al., 1997). It should be noted that the correlation between sickness as measured by subjective method (for example SSQ) and objective measures of after effects of VR simulation is generally insignificant (Stanney et al., 1998), which implies that it is beneficial to apply both subjective and objective measurements in order to comprehensively understand the sickness level occur with VR simulation exposure. Due to the resources limitation, only postural stability tests were adopted in this study.

2.1.3 Factors influencing Cybersickness

Much research has been done to identify the causing factors that may contribute to the generation of cybersickness. From the literature, there are many possible potential

causing factors in producing cybersickness, for example, gender, age, susceptibility to motion sickness, field of view of the VR display, lag, update rate of the VR system and so on (reviewed by Kolasinski, 1995; Stanney et al., 2002). In this study, we focus on studying the relationships between visual stimuli inside VE and the level of cybersickness since visual stimuli is the major stimuli in VR simulation In particular, in this study, the effects of navigation velocity on level of cybersickness are investigated. Navigation velocity is defined as one critical component of Spatial Velocity (So et al., 2001a). This will be addressed in the later section of this chapter.

2.2 Major theories on cybersickness

To study cybersickness, one important issue should be discussed, i.e., how does cybersickness generate? What causes cybersickness? There are several theories on explaining the generation of cybersickness. The four most prominent theories are presented here, including sensory rearrangement theory, postural instability theory, eye movement theory and poison theory.

2.2.1 Sensory rearrangement theory

Sensory rearrangement theory proposed by Reason (1978) is the oldest and most accepted theory used to describe the etiological processes that occur with cybersickness. Basically, it is saying that the human body doesn't know how to deal with the discrepancies between different senses from vestibular system and visual system, and the mismatch causes internal conflict can not be resolved and eventually results in the symptoms associated with cybersickness.

Human beings rely on vision system a great deal when interpreting motion. The other most important inertial motion detector for human is the vestibular system in the inner ear. It is still a mystery how human subjects combine visual and vestibular inputs for their self-motion perception. Problems of disorientation and nausea in VR system have been ascribed to the discrepancy between visual and vestibular information about body orientation and motion. Under ordinary circumstances, there is a correspondence between what is sensed from visual system and the physical representation of the stimulus from vestibular system. However, in VEs, commonly, the visual system senses motion without corresponding stimulation of the vestibular system.

More specifically, when a VR user is wearing a HMD (Head mounted display), he or she is often immersive with a visual stimuli indicating motion inside a VE. For example, the optical flow patters of roads, buildings and moving objects in a VE provide the user a sense of moving in a certain direction. However, since he or she is usually physically stationary during VR simulation exposure, there is often no concordant physical motion to stimulate the vestibular system. Therefore, the sensory conflict between what one sees and what one feels, or the integrated visual and vestibular information don't agree with one's prediction based on the past experiences.

In VR simulations, conflicts between vestibular and visual signals could possibly occur when (1) there exists visual stimuli in the absence of vestibular stimuli; (2) there is a delay between vestibular signal and corresponding movements of a visual scene; (3) the motions of a visual scene are distorted compared with head movements.

2.2.2 Postural instability theory

Destructions of balance been related to motion and unusual force environments. A longitudinal study by Dichgans and Brandt (1978) implied that the maintenance of stable posture in a moving visual field required the correct awareness of the consequences of body movement.

The postural instability theory was developed by Riccio and Stroffregen (1991). They claimed that for a human being, one of a primary behavioral goal is to maintain postural stability in the environment. There are several sources of prolonged instability including low-frequency vibration, weightlessness, changing direction of gravity and the support surface and altered specificity, for example, immersion inside VE. Riccio and Stroffregen pointed out that "*Postural instability will result whenever an animal links its control to patterns of stimulation that have ceased to be specific to those environmental conditions for which the control is appropriate.*" (quoted from Riccio and Stoffregen, 1991)

Whenever the environment changes unexpectedly or significantly postural instability theory states that the cause of motion sickness or cybersickness is prolonged postural instability. It is hypnotized that the severity of motion sickness will be scaleable directly to the duration and magnitude of postural instability experienced (Hamilton et al., 1989; Kennedy et al., 1993; Cobb, 1999).

2.2.3 Eye movement theory

Eye movement theory is saying that eye movements, specifically, optokinetic nystagmus (OKN) will cause cybersickness. OKN is produced by moving repetitive patterns in the visual field. It is a complex ocular motor reflex that allows us to adequately follow different images when we keep our head steady. OKN is type of eye movements characterized by a series of smooth movements in the same direction of a moving visual scene, interspersed with rapid movements in the opposite direction.

Ebenholtz et al. (1994) proposed that eye movements play an important role in the development of motion sickness. They suggested that ocular muscles' traction mediated by vestibular nuclei during OKN may stimulate the vagus nerve to induce motion sickness symptoms. Their hypothesis based on findings of extensive neural connection between vestibular nuclei and eye muscles. Since that, Hu and Stern (1998) investigated the relationships of the frequency of OKN and the severity of optokinetic rotation-induced motion sickness. The results from this research demonstrated that more rapid eye movements indexed by higher frequency of OKN are related to the development of symptoms of motion sickness.

Flanagan and his colleagues (2001) reported their experiment on investigating OKN, vection and motion sickness. They evaluated two current notions concerning the etiology of motion sickness (i.e., the eye movement hypothesis and the sensory rearrangement hypothesis). In their study, conditions that manipulated the degree of OKN and/or ego vection were investigated. These eye movement and illusion of self

motion responses were elicited with whole field stimulation in a vertically stripped drum and modulated with fixation and/or a restriction of the field of view. Measures of OKN, ego vection and motion sickness were recorded under the various conditions. Both visual field restriction and fixation reduced circular ego vection, while only fixation significantly reduced OKN. Conditions of fixation resulted in greater reductions in motion sickness than conditions of visual field restrictions. These findings lend considerable support to the eye movement hypothesis, but do not convincingly rule out the sensory rearrangement idea. A model incorporating a synthesis of these two phenomena in the provocation of motion sickness was discussed in their study.

2.2.4 Poison theory

The poison theory attempts to provide explanation for why motion sickness and cybersickness occur from an evolutionary point of view (Treisman, 1977). The theory suggests that the ingestion of poison causes physiological effects on the vestibular and visual systems. Thus cybersickness is human's response to protect the body when the body believes it's been poisoned. However, vomiting is not common in terms of cybersickness and also this theory does not explain why same stimuli don't have the same response on different people.

2.2.5 Summary of theories

In summary, sensory rearrangement theory believes the disagreement between vestibular and visual senses generate cybersickness. Eye movement theory believes the occurrence of produces sickness. Postural instability regards motion is not matched to conditioned beliefs and poison conflict theory believes body takes mismatched sensory cues as a belief that it is being poisoned. Among those four theories, sensory rearrangement theory is the most popular and accepted theory in the motion sickness research filed. Postural instability and eye movement theory are proposed later, more studies are needed to conduct in order to test and verify these two theories. On-line techniques of measuring postural instability and eye movements are developing during the past 10 years. For poison theory, it seems hard to validate the viable of this theory since the theory is too vague.

Even though sensory rearrangement theory is the most widely accepted theory on cause of cybersickness, there are still several problems with it. The first issue is that the theory does not allow for effective prediction of cybersickness. There is no reliable formula based on sensory inputs and conflicts that can be used to determine which situations will produce sickness and what is the severity level of induced sickness. Second, this theory doesn't locate the neural processing centers that would account for such a response and it is unlikely that there is an undiscovered neural processing center that is dedicated to this particular response. Nevertheless, this study believes that based on sensory rearrangement theory, visual scene movements play a very important role in producing cybersickness. In some of the experimental work, postural stability tests were also adopted to partially test the validity of the postural instability theory.

2.3 Relationship between visual scene movements and cybersickness

According to the sensory rearrangement theory, there are two important signals involved in VR simulation: visual signal and physical movement signal. In this study, we focus on the visual stimuli, and physical movements of users are controlled, in another word, users are physically stationary during exposure, so that the visual stimuli are the dominant causing essence in generating cybersickness. Visual scene movement in VEs can significantly cause the human sensation of illusion of self-motion; consequently, causing the internal sensory conflict, hence scene movement can be an important contributing factor affecting the level of cybersickness. In a typical VR simulation, there is a strong sense of self-motion driven through moving visual imagery while immersed in VEs. This illusion of self-motion, named vection is highly nauseogenic. Vection can occur in real life, such as looking out the window of a stationary train, when the adjacent train starting to move, the one seated in this stationary train would feel himself/herself moving towards the opposite direction.

Studies on illusion of self-motion with rotating scenes (Hu et al., 1989, 1997; Kennedy et al., 1996) have shown that visual-induced sickness symptoms are mainly caused by viewing movements of spatially contrasted patterns regardless of the meaning behind the patterns. These illusions of self-motion effects have often been seen in Virtual Environments as well. Immersive virtual environments with wide field of view displays or HMD where fewer references to a static world exist are prone to causing . The changes in optic flow provided by the visual system provide both translational and

rotational information. In a standard environment, these changes in optic flow would be accompanied by corresponding vestibular information. However, in a VE, the vestibular information is not available for consistent with visual information. It is the result of this effect that forms the basis for the sensory rearrangement theory of motion sickness.

In 2002, Hettinger made an extensively review and summarized four major physical properties can possibly affect the perception of self-motion in VEs. The four factors are 1)size of the visual field of view; 2) velocity of the visual stimuli; 3) spatial frequency of the visual stimuli; 4) presence of background and foreground information. In this study, field-of-view and presence of background and foreground information is out of the research interest, and we only on the spatial frequency and the velocity of the visual stimuli.

Velocity of the visual stimulus is a very important visual factor influencing the intensity and velocity of illusory self-motion. Howard (1986) reports the general finding that the velocity of illusory self-rotation is proportional to visual stimulus velocity up to value of approximately 90deg/sec, although this relationship is influenced by the spatial frequency of the stimulus pattern. Similarly, Brandt et al. (1973) observed that perceived velocity of illusory self-motion in circular vection is linearly related to stimulus velocity up to about 90 to 120deg/sec, beyond which perceived illusory self-motion velocity lags behind stimulus velocity. Kennedy et al. (1996) found the onset time of vection to occur was also affected by the speed of the visual stimuli. As the stimulus speed increased from 20deg/sec to 130deg/sec, the onset time of vection is reduced, and then kept stable

at speeds between 130deg/sec to 160deg/sec, and increased at speeds between 160deg/sec to 220deg/sec.

Scene complexity as measured by the luminance change, i.e. spatial frequency, can affect the self-motion perception. Diener, Wirt, Dichgans and Brandt (1976) provide psychophysical support that human observers perceive self motion velocity affected by spatial frequency of the visual stimuli. Diener et al.'s results were consistent with the findings obtained by Owen and his colleagues (e.g. Owen, Wolpert and Warren, 1983; Warren, Owen, and Hettinger, 1982) who observed that "edge rate" information was more complete than global optical flow in determining observer's judgments of self-motion. Edge rate can be defined as the number of edges or discontinuities that pass across the observers' visual field per unit time. Edge rate is affected if systematic changes in texture density occur (Wickens, and Hollands, 2000). Hence, this "edge rate" also contains spatial frequency information (i.e. reflected by texture density) as well as motion velocity. Furthermore, Hu et al. (1989) reported rotating speeds of drum changed from 15deg/sec to 90deg/sec, motion sickness increased, peaked (60deg/sec) and declined. Hu et al. (1997) also conducted experiment using striped rotating drum and the results indicated severity of vection-induced motion sickness is affected by differential spatial frequencies of the strips of the rotating drum. Motion sickness level increased with spatial frequency up to 24 stripes and then dropped later on. These empirical evidences show strong relationship between spatial frequency as well as rotating speed and the level of visually induced motion sickness.

In summary, we strongly believe spatial frequency and the velocity of the visual stimuli in VEs significantly influence the sensation of self motion perceived by users, which provocate the development of cybersickness. We won't eliminate the effects of field-of-view and the presentation of background and foreground, however, due to the resource limitations, they are not studied in this study. Actually, this could be the future work and extension of the current work. Previous studies (Yuen, 2002) have been done on exploring the effects of spatial frequency on the level of cybersickness. In particular this study will focus on investigate the role of navigation velocity on the level of cybersickness.

As proposed by So et al. (2001a), Spatial Velocity (SV) can quantify the visual scene movements inside a VE. The proposed SV metric is a measure of the rate of movement of contrasted information perceived by a subject during a VR simulation. SV is attempting to decompose the two main elements of a visual stimulus in VR simulation that are believed to provocate self motion in VEs, i.e., velocity and spatial frequency of the visual stimuli. SV has two components: scene complexity and navigation velocity. Scene complexity perceived by participants during a VR simulation is measured as the average spatial frequencies (SFs) in the horizontal, vertical and radial axes. Navigation velocity is calculated by the root-mean-square values of the scene movements on six different axes (vertical, lateral, fore-and-aft, pitch, yaw and roll). The more detailed about Spatial Velocity will be reviewed in the next section. Figure 2.3 illustrate how visual scene movements as measured by Spatial Velocity affect the level of

cybersickness.

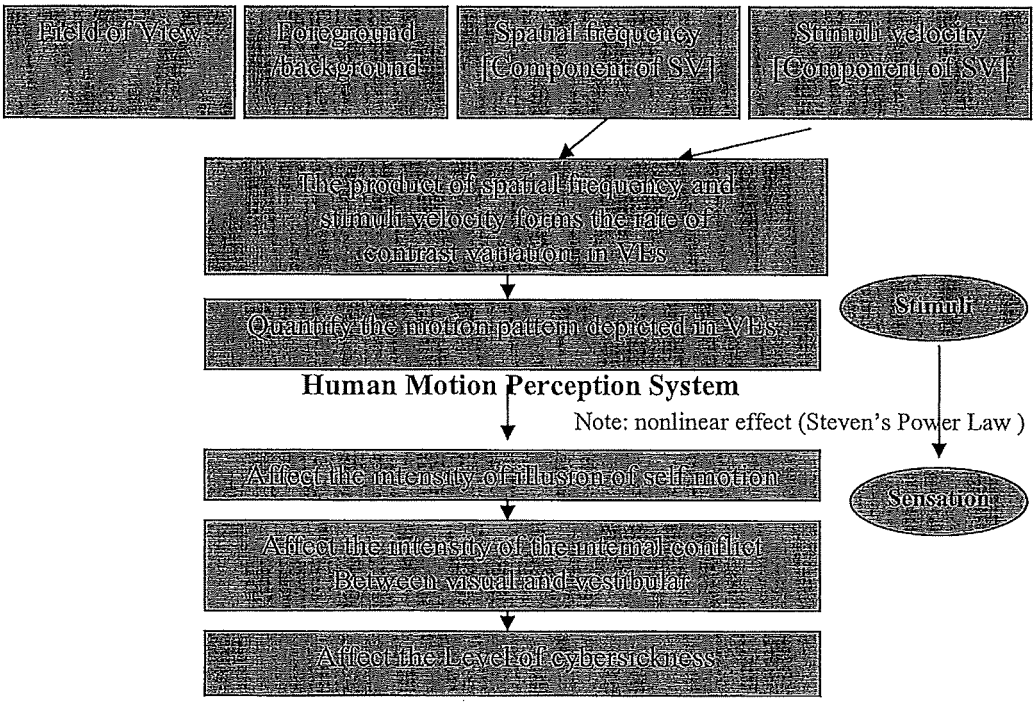

Figure 2.3 Illustration of visual scene movements affecting the level of cybersickness

According to Steven's power law, the strength of sensation is a nonlinear function of the intensity of the stimulus. Hence, it is possible that illusion of self motion is a nonlinear function of scene movements, thereafter, scene movements possibly has a nonlinear effects on the level of cybersickness.

2.4 Review on measurement of scene movement in a VE

Spatial Velocity (SV) is proposed to quantify visual stimuli (So et.al, 2001a). The proposed SV metric is a measure of the rate of movement of contrasted information

perceived by a subject during a VR simulation. Movements of spatially contrasted pattern (e.g. black and white stripe) have previously been shown to induce sense of self-motion illusion (vection) and symptoms of motion sickness. This forms the theoretical basis for the SV metric as already discussed in the previous section.

2.4.1 Spatial Velocity

This proposed SV metric (So et.al, 2001a) has two components as mentioned in the previous part: scene complexity and navigation velocity. These two components are multiplied to form the rate of luminance variation that is perceived by a participant when he or she navigates through a VE:

The rate = (average spatial frequency, SF, along that axis) * (navigation velocity, V, along that axis).

This rate is referred to as the spatial velocity (SV) for that axis. It combines the scene complexity of a visual scene (SF) and its movement (V) relative to the participant.

Spatial velocities for all six motions are calculated as

$$\begin{bmatrix} SV_{fore-and-aft} & SV_{roll} \\ SV_{lateral} & SV_{yaw} \\ SV_{vertical} & SV_{Pitch} \end{bmatrix} =$$

$$\begin{bmatrix} SF_{rad} & SF_{horizontal} & SF_{vertical} \end{bmatrix} \times \begin{bmatrix} V_{fore-and-aft} & V_{roll} \\ V_{lateral} & V_{yaw} \\ V_{vertical} & V_{pitch} \end{bmatrix}$$

Where $SV_{fore-and-aft}, SV_{lateral}, SV_{vertoca;}, SV_{roll}, SV_{yaw}, SV_{pitch}$ are the spatial velocities of the fore-and-aft, lateral, vertical, yaw, pitch, and roll motions; $SF_{rad}, SF_{horizontal}, SF_{vertical}$ are the spatial frequencies of scene components in the horizontal, radial, and vertical axes; and $V_{fore-and-aft}, V_{lateral}, V_{vertoca;}, V_{roll}, V_{yaw}, V_{pitch}$ are the navigation velocities in the six axes.

Since Spatial Velocity consists of the two components, each of them will be addressed respectively in the following part.

2.4.2 Scene Complexity

2.4.2.1 Luminance components and chrominance components

In order to define scene complexity, we can consider the visual scene in a video, which is the same as that shown through HMD in a Virtual Environment. A video signal consists of two signals (Madisetti and Williams, 1998) - the luminance which carries with the brightness information and chrominance which carries the color information. Luminance is that part of a video signal relating to the degree of brightness at any given point in the video image. If luminance is high, the picture is bright and if low, the picture is dark. Changing the chrominance does not affect the brightness of the picture. Chrominance is the color information contained in a video signal separate from the luminance component, consisting of the hue (phase angle) and saturation (amplitude) of the color subcarrier signal. Based on the above, it is reasonable to define scene

complexity in virtual environments to have two basic components: the luminance component and the chrominance component.

To measure the scene complexity in a virtual environment, we need to determine both the chrominance component and the luminance component. However, from the literature we know that the chrominance component may not play a significant role in terms of the perception of visual motion in human brain. Human central visual system is separate into P pathway which indicating color, form and detail signals and M pathway which indicating visual motion signals. This two visual systems theory (Held et al., 1967) suggested that motion is detected by the ambient vision, i.e, M pathway, which is insensitive to color.

In order to verify this hypothesis, an experiment (Yuen, 2002) was conducted to study the effects of color on the levels of cybersickness. Four similar sea-front Virtual Environments with different color combinations of sea and ground were built. They were developed so that their grayscales look more or less the same. This study aimed to investigate the effects of different colors with similar spatial frequency on the level of cybersickness. The result showed no significant effects of color were found influencing the level of cybersickness. Therefore, it is suggested that only the more important component i.e., luminance is used to represent the scene complexity in the virtual environment. In quantifying the scene complexity in the virtual environment, between the chrominance and luminance factors, luminance seems to have a more important effect than the chrominance factor. As the method of quantification for the scene

complexity is still in a very early stage, for the ease of study, chrominance factor is neglected in this stage.

2.4.2.2 The use of spatial frequency to measure luminance component of scene complexity

Scene complexity perceived by participants during a VR simulation is measured as the average spatial frequencies (SFs) in the horizontal, vertical and radial axes. These three average SFs are calculated from sampled snapshots of the Virtual Environment along the navigation path.

Spatial frequency is a measure of how rapidly a property changes in space. A commonly used form of visual stimulus consists of vertical bars where the lightness varies according to a sinusoidal function. In this simple case the spatial frequency of the stimulus is just the frequency of the sinusoid used to generate the pattern. In general stimuli with fine detail including sharp edges have high spatial frequency while those where the stimulus properties change more slowly in space have low spatial frequency.

More detailed explanation of how to calculate the spatial frequency of one snapshot in the VE simulation is addressed below (So et al., 2001a). During a simulation, a snapshot is captured. By using graphical software ImageMagick™, the changes of gray scale values along each row and column are then extracted (0 is black and 255 is white). Fast Fourier Transforms (FFTs) are then applied to this extracted gray scale history, and the power spectral density (PSD) function of this gray scale series is obtained. Hence, the

Spatial Frequency (SF) of row or column is calculated. This process is then repeated for all the rows and the average SF is the $SF_{horizontal}$ of this snapshot. When the whole process is repeated for all the columns of this snap shot, the average $SF_{vertical}$ is calculated. Finally, the SF_{radial} is calculated as the geometric mean of the $SF_{horizontal}$ and $SF_{vertical}$ as follows,

$$SF_{radial}^2 = SF_{horizontal}^2 + SF_{vertical}^2$$

In order to obtain the average spatial frequencies of the whole VR simulations, it is necessary to capture certain number of snapshots. In 2002, Yuen reports the optimized number of samples needed is from 20 to 60 snapshots. Taking the average of the spatial frequencies of the sample snapshots, the average spatial frequencies of the VR simulation is obtained.

2.4.3 Navigation Velocity

The speed of movement through a virtual environment determines global visual flow (i.e. the rate at which objects flow through the visual scene). The rate of visual flow influences vection and has been shown to be related to the incidence of simulator sickness (Mccualy and Sharkey, 1992; Hettinger, 2002).

Navigation velocity is calculated by the root-mean-square values of the scene movements on six different axes (vertical, lateral, fore-and-aft, pitch, yaw and roll; So et al., 2001). Figure2.4 illustrates six axes adopted in this study.

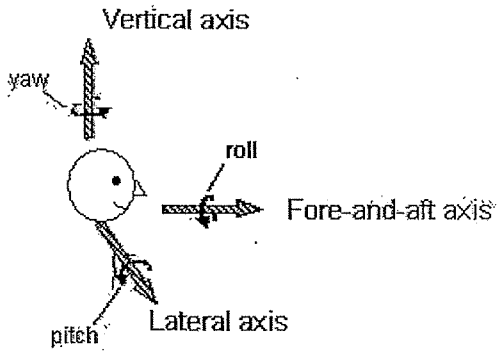

Figure 2.4 Illustration of navigation velocities in six axes

2.4.4 Benefits of the "Spatial Velocity" metric

Empirical experiment data were reanalyzed to determine the effects of SV on the rated level of cybersickness (So et al., 2001a). Significant correlations were found between SV and the level of cybersickness ($p<0.001$) from the preliminary data. The initial results showed that, as SVs (either increased scene complexities or increased navigation velocities) increased in the fore-and-aft axis, both the nausea rating and the SSQ total score increased.

With the SV metric, it is now possible to quantify the visual stimuli inside a VE, and the effects of visual scene movement on levels of cybersickness can be systematically studied. Experiments can be conducted to establish the relationship between the intensity of as measured by SV and the rated level of cybersickness.

2.5 Research literature concerning effects of navigation velocities on cybersickness

As addressed in the previous section, in this study, we are interested in studying the effects of navigation velocity on the level of cybersickness. How far or slow should a user virtually navigate through a VE without causing severe level of cybersickness? In section 2.3, the literature on the relationships between navigation velocities and illusion of self motion have been reviewed. These literatures reveal the important impacts of navigation velocities on the illusion of self motion of human beings and hence, will affect the level of cybersickness experienced by the user of VR simulations. A review of literature indicates that there are not many studies investigating the effects of different level of navigation velocities on the level of cybersickness in VEs. However, there are some relevant studies have been done in the field of visually induced motion sickness.

2.5.1 Past studies of navigation velocities on visually induced motion sickness

In 1989, Hu et al. reported a study on investigation of visually induced motion sickness as a function of speed of rotating drum. Rotating drum is a drum with alternative black and white stripes and it is the commonly used in the study of visually induced motion sickness. Four rotating speeds in yaw were used: 15, 30, 60 and 90 deg/sec. Their results indicated motion sickness symptoms increased as rotating speed increased up to 60deg/sec, and decreased at 90deg/sec.

2.5.2 Past studies of navigation velocities on cybersickness in VEs

Regan (1995) conducted an investigation into levels of cybersickness of immersive VR. In this study, participants were grouped into classes, i.e., one group were instructed to interact with the VR simulation as fast as they could and the other group were free to

control the speed of interaction with the VR simulation. Regan found two groups reported statistically the same levels of SSQ scores. So et al. (2001b) reported a study on investigating the effects of different navigation speeds in fore-and-aft axis on cybersickness. In their study, an outdoor city VE was used, and the dominant navigation was in the fore-and-aft axis. Eight levels of speeds in fore-and-aft were used: 3, 4, 6, 8, 10, 24, 30 and 59 m/sec. The results of this study indicate both the nausea ratings and vection ratings increased significantly with speeds increasing from 3m/sec to 10m/sec, after which, the effects stabilized. For the SSQ scores, navigation speeds only significantly affect oculomotor subscore.

2.6 Research literature concerning comparison of scene movements in different axes on cybersickness

According to sensory rearrangement theory, navigation inside VEs is an essential causal factor to cybersickness. Besides theoretical support that navigation in VEs can cause cybersickness, empirical study also proved the importance of scene movement to the generation of cybersickness. So et al. (1999) conducted experiments and reported that the presence of scene movement could produce more than double the level of cybersickness compared with VR simulation without scene movement. This result indicated that user experienced significantly more sickness while visually navigating inside VEs than no navigation condition. These findings imply that navigation is one of the critical causing factors in producing cybersickness.

Based on the fact that visual scene movements in fore-and-aft axis causing cybersickness significantly, since navigation in VR simulation can possibly occur in six axes, i.e., three rotational axes (roll, yaw and pitch) and three translational axes (fore-and-aft, lateral and vertical), as we already mentioned, one question is still waiting to be answered, how about visual scene movements in the other axes besides fore-and-aft axis? As we can see in section 2.5, literature concerning effects of navigation velocities on cybersickness usually limited to one axis in one study. Will visual scene movements in other motion axes have the same effects on cybersickness as we found with visual scene movements in fore-and-aft axis? What are the differences between scene movements in different axes?

From the literature, researchers working on motion sickness have involved studying the effects of six motion axes (exactly the same six axes mentioned before). And, these studies show significant effects of navigation in different axes on motion sickness.

Griffin and his colleagues (1986) studied sea sickness by investigating the effects of individual six motion axes. Griffin Identified a dominant axis used to be able to establish a prediction model for sea sickness based on measurement of motion in vertical axis. Turner and Griffin (1999) found motion sickness occurred in road transportation were mainly associated with motion in lateral axis. Golding and Kerguelen (1995) reported significant different impact of horizontal oscillation vs. vertical oscillation on motion sickness. All these researches confirm that motion axis has significant effects on motion sickness.

We adopt the similar approach here to study the effects of navigation in VEs on the level of cybersickness, in other words, the effects of three different translational navigations and three different rotational navigations are considered and investigated separately in our study.

In fact, Lo and So (2001) have studied and published the effects of three rotational navigations on the level of cybersickness. They conducted an experiment to study the relationships between visual scene oscillation in yaw, pitch and roll axes in a VE and the rated level of cybersickness. In this study, a sine-wave oscillation was used and the r.m.s speed of scene oscillation was 30deg/sec and the range of oscillation was $\pm$ 60deg. Lo and So's result indicated that scene oscillations in pitch, yaw and roll axes at 30deg/sec were shown to significantly increase the rated level of cybersickness and suggested that there was no dominant rotational axis of virtual scene movement contributing to cybersickness.

However, similar study on investigations of comparing navigation in three different translational axes in a same VE cannot be found.

2.7 Summary

From the literature, cybersickness can have a strong side effect on the user. Around 85% of the user of VR systems report motion sickness like symptoms. Cybersickness definitely becomes a most critical problem affecting the development of VR technology. Sensory rearrangement theory supported that cybersickness is a visually induced motion

sickness. Lots of literatures also show that visual scene movements play a very important role in producing cybersickness since scene movement causes illusion of self motion in VEs.

Furthermore, Spatial Velocity can be used to quantify the visual scene movements associated with a VR simulation. Navigation velocity as one component of Scene Velocity, is an important factor which contributes to cybersickness. Navigation velocity is defined in one of six axes (i.e., three translational: fore-and-aft, lateral and vertical; three rotational: yaw, pitch and roll).

Comparisons of effects of navigation in three rotational axes have been investigated in a past study where r.m.s speeds of 30deg/sec in yaw, pitch and roll were used. The results of this study indicate that, navigating in VEs at 30deg/sec, there is no significant difference among three rotational axes in producing cybersickness. However, similar study on investigations of comparing navigation in three different translational axes in a same VE cannot be found. This experiment will be firstly conducted to complement Lo and So's study. Furthermore, the results from these two studies can provide us the implications that what motion axes we need further explore. If the results from these two studies indicated that navigating in different motion axes may produce significantly different levels of cybersickness among users, then we are motivated to further manipulating the navigation velocities in different axes.

On the other hand, current studies of effects of different level of navigation velocities on cybersickness are only limited to fore-and-aft axes. How about the effects of different

navigation velocities in other axes on the level of cybersickness? Will there exist similar patterns as what found in fore-and-aft axis? We aim to extend the study scope to other different axes as well.

Chapter 3 Effects of scene movements in different translational axes on the level of cybersickness (Experiment 1a, 1b)

3.1 Motivation

As addressed in section 2.6, from the literature, researchers working on motion sickness have involved studying the effects of six motion axes. Significant effects of navigation in different axes on motion sickness were found. Lo and So (2001) have conducted an experiment to compare the effects of visual scene oscillation in rotational axes in Virtual Environment and the rated level of cybersickness. In Lo and So's study, scene movements were presented in a sine wave oscillation in three different rotational axes (pitch, yaw and roll) respectively and the r.m.s velocity was 30 deg/sec. Lo and So's result indicated that scene oscillations in the pitch, yaw and roll axes were shown to significantly increase the rated level of cybersickness and suggests that there was no dominant rotational axis of virtual scene movement contributing to cybersickness. However, there is no peer study available on investigating the differences among the effects of scene movements in different translational axes in VEs on level of cybersickness.

The purpose of this chapter is to investigate the effects of translational navigation in three different axes (i.e., fore-and-aft, lateral, vertical) on the level of cybersickness in a VE. In this study, we aimed to search the dominant influencing axes on cybersickness

among the three translational axes. It was hypothesized that a VE without virtual navigation would produce lower levels of sickness. Therefore, no navigation as a control condition was also used to compare with these three navigation conditions. This study therefore complements the studies of the effects of scene movements in different axes in VEs. It is also should be noted that in this study, navigation velocity is controlled at a certain level.

3.2 Methodology

3.2.1 Participants

Thirty-two male Chinese and thirty-two female Chinese volunteers participated in the experiments. These subjects were university student members from 18 to 35 years old. Each of them was paid HK$60 as compensation for his/her time for each experimental session. All participants were consented volunteers who were healthy and free of medication and illness. The Human Subject and Research Ethics Committee at the Hong Kong University of Science and Technology approved the experiments. It has been reported gender can have a significant effect on susceptibility to motion sickness (Kennedy et al., 1995), hence gender difference was also investigated in the experiments.

3.2.2 Apparatus and virtual reality simulations

The virtual scene was constructed using a Virtual Reality authoring software (World Tool Kit, Release 9) running on a Silicon Graphics Onyx II (Silicon Graphics, Inc.)

workstation. The program was written in C++ language. The VE was presented on a VR4 (Virtual Research Systems, Inc.) LCD Head-Mounted Display (HMD) with a field-of-view of 48 degree in horizontal and 36 degree in vertical. The images were presented on the HMD in binocular mode. A Polhemus 3-Space magnetic tracker (Polhemus, Inc.) was used to measure the head position and orientation at a rate of 30/sec during the VR simulation. Figure 3.1 showed the apparatus used in this experiment.

Figure 3.1 Apparatus used in Experiment 1a & 1b

The Virtual Environment consisted of a large room with 40m in length, 40m in width and 40m in height. Four Virtual Reality simulation conditions were used. In control condition, participants experienced no navigation. For the other three simulation conditions, participants virtually navigated inside the room along three different translational axes (see Figure 3.2): fore-and-aft, lateral or vertical. The navigation path was presented in sinusoidal wave movements with the amplitude of 18m, the root mean

square (r.m.s) velocity was 15m/s and the visual scene motion frequency was 0.12 Hz. The average frame rates were 30 frame/second in all the four simulation conditions. Figure 3.3 showed four example snapshots of VE used in this experiment.

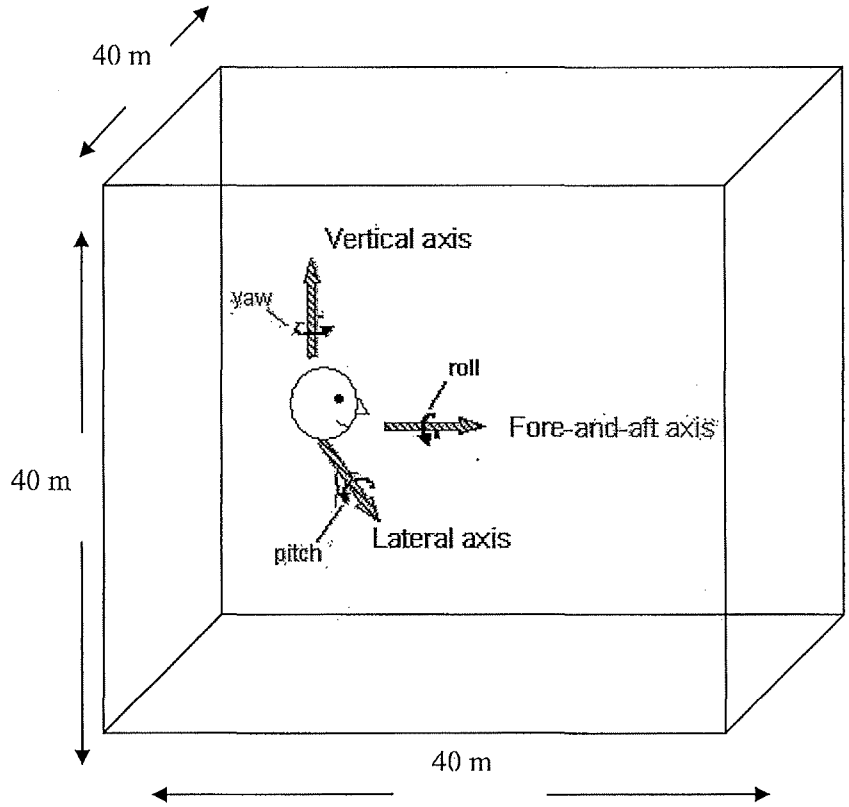

Figure 3.2 Illustrations of Virtual Environment and Virtual Reality simulation conditions used in the experiments. Four Virtual Reality simulations conditions were used: no navigation, navigation along fore-and-aft axis, navigation along lateral axis and navigation along vertical axis.

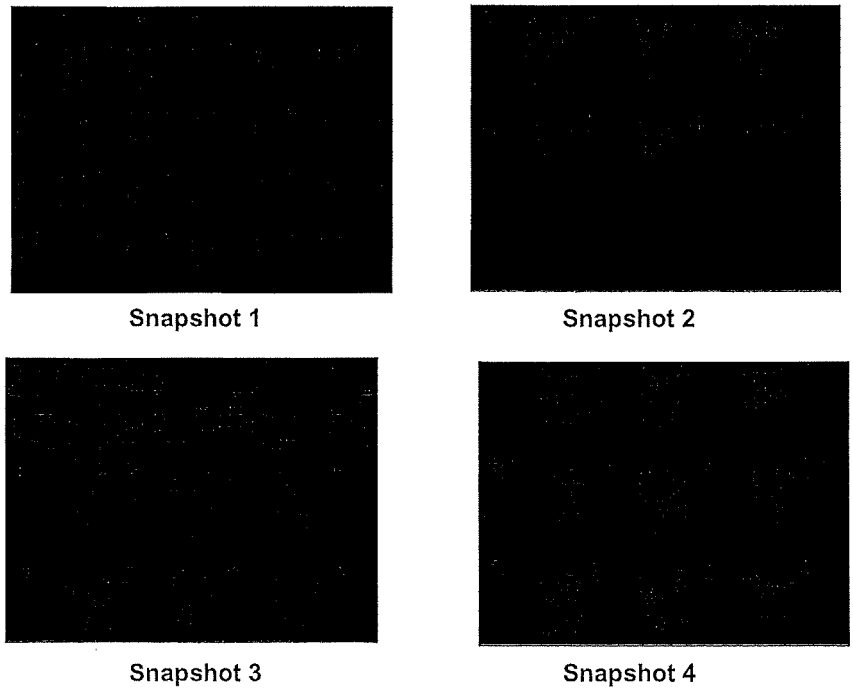

Figure 3.3 Four snapshots of virtual environment used in Experiment 1a & 1b.

3.2.3 Experimental design

The experiments investigated four levels of translational navigation: no navigation (control condition), fore-and-aft translational navigation, lateral translational navigation, and vertical translational navigation. In the meanwhile, gender difference was also considered.

Two experiments were conducted. Experiment 1a was a full factorial between-subject design. Totally 64 (32 male and 32 female) participants took part in Experiment 1a, and each participant was randomly assigned to one navigation condition. Experiment 1b was full factorial within-subject design. Out of 64 participants in Experiment 1a, 6 male and

6 female volunteers participated in all the four navigation conditions with at least four weeks separation. Each subject's exposure to a condition took 30 minutes for both Experiment 1a and Experiment 1b.

There were several reasons to conduct two experiments with different design. Firstly, the second experiment was expected to further confirm or validate the results from the first experiment. Secondly, the tradeoffs between between-subject design and within- subject design motivated us to conduct both two designs. Between-subject variability is usually larger than within-subject variability, it will be more likely to detect significant differences in within-subjects design only due to different level of independent variable rather than due to large inter subject variability. However, within-subject design has one disadvantage - the possible existence of learning effect since subjects were required to participate in all the four conditions and hence they were immersed in four VR simulation sessions. Regan and Price (1994) reported that repeated exposure to the same VE with separation of less than seven days could significantly affect the levels of cybersickness, while Cobb et al. (1999) also reported that repeated exposure to the same VR simulation in consecutive weeks could reduce the level of cybersickness. Haworth and Hill (1999) concluded that there must have been physiological habituation to the cybersickness. Therefore, the inter sessions interval was set to at least four weeks to minimize the potential biases caused by learning effect.

3.2.4 Procedures and measurements

Before each exposure, participants were asked to read and sign a consent form. And then participants were required to complete a Motion Sickness Susceptibility Survey (MSSS, Appendix F) which was used to indicate the participants' sensitivities to motion sickness. The subjects' susceptibilities to motion sickness were then recorded and the corresponding information were used to balance subjects' susceptibilities among different navigation conditions to avoid that, in one particular condition, subjects were biased to have more or less susceptibilities on motion sickness than those in other conditions. Then, participants were asked to complete a pre-exposure Simulation Sickness Questionnaire (SSQ, Appendix G). It should be noted that all participants with a pre-exposure SSQ of more than 2 slight symptoms or a pre-exposure SSQ total score of more than 10 were asked to take a rest for 5-10 minutes with their eyes closed. After that, the participants were asked to fill in another pre-SSQ. If the pre-exposure SSQ total score was less than 10, then the experiment proceeded. However, if the pre-exposure SSQ total score was still more than 10, then the participants were asked to come back for another date. Kenney and Stanney et al. (1999) excluded anyone with a pre-SSQ total score of more than 10 in their experiments.

Then participants were asked to have the pre-exposure posture stability tests. Subject's posture stability performance was recorded by posture test program. Duration of balance keeping and degree of head swinging were measured. Scores for each subject on each test were based on average performance over four trials on SR, where the scores were based on the mean of three trials on SOPL and SONL (Hamilton, 1989).

Before experiments started, participants were educated to distinguish vection from perceived speed of the surround scene. They were reminded to rate only the level of vection experienced during VE exposure. Kennedy et al. (1996) reported that participants could reliably separate vection from perceived speed. Then 30 min Virtual Reality simulation was given. During the 30 minutes Virtual Reality simulation, participants were asked to keep sitting in an up-right posture. In the control condition "no navigation", participants were watching a stationary Virtual Environment. During the immersive exposure, participants were also asked to turn their heads and look left or right. This was repeated once every 75 seconds alternating between left and right so as to encourage participants to be more involved in the VE. These movements are suggested to have no effect on levels of cybersickness as the viewpoint was moving according to the movement of the head. Therefore, there is no conflict between the stimuli given to the vestibular and visual system. According to the sensory rearrangement theory, it will not cause any sickness. It should be noted that in the "no navigation" condition, participants were also required to turn left or right. Although, restrictively, participants did see some scene movement, we still treated it as "no navigation" condition since compared with other three navigation conditions with r.m.s speed of 15m/sec, the effect of such yaw movements could be relatively neglected. At five-minute intervals, participants were asked to rate verbally their symptoms of nausea on a seven-point scale (Appendix A) and their sensation of vection on a 4-point scale (Appendix C).

After the exposure of VR simulation, participants were asked to complete a post-exposure SSQ (Appendix H). And also they were asked to participate in the post-posture

stability tests. During the simulation, if a participant reported the nausea rating of 6 (that is *moderate nausea, want to stop*), then the VR simulation was terminated and the participant was asked to complete the post-exposure SSQ. A score of 6 was assigned for the remaining verbal rating reports.

3.3 Results

As mentioned before, two experiments were conducted: one was between-subject design and the other was within-subject design. Data on nausea ratings, vection ratings, SSQ measurements and postural stability performance measurements obtained in Experiment 1a passed the test for normal distribution (See Appendix D). In Experiment 1b, data on nausea ratings, vection ratings and postural stability measurements also followed the normal distribution, but data on SSQ measurements did not pass normal distribution test. Therefore, parametric statistical analysis was applied for the normal distribution data while non-parametric analytical methods would be applied to SSQ data of Experiment 1b. Results for Experiment 1a (between-subject design) and Experiment 1b (within-subject design) respectively were reported. SAS 8.01 and SPSS 11.0 were used to analyze the data.

3.3.1 Results collected in Experiment 1a

3.3.1.1 Nausea ratings and vection ratings

The mean vection ratings and nausea ratings with standard deviations obtained with the four navigation conditions were shown in Figure 3.4 and Figure 3.5. Figure 3.4 indicated vection ratings increased with exposure time for the first 15 or 20 minutes while kept stable later on in three navigation conditions. Figure 3.5 indicated that nausea ratings increased with increasing exposure time.

The correlations between nausea rating and vection rating within same duration and within same navigation condition were shown in Table 3.1 and Table 3.2 respectively.

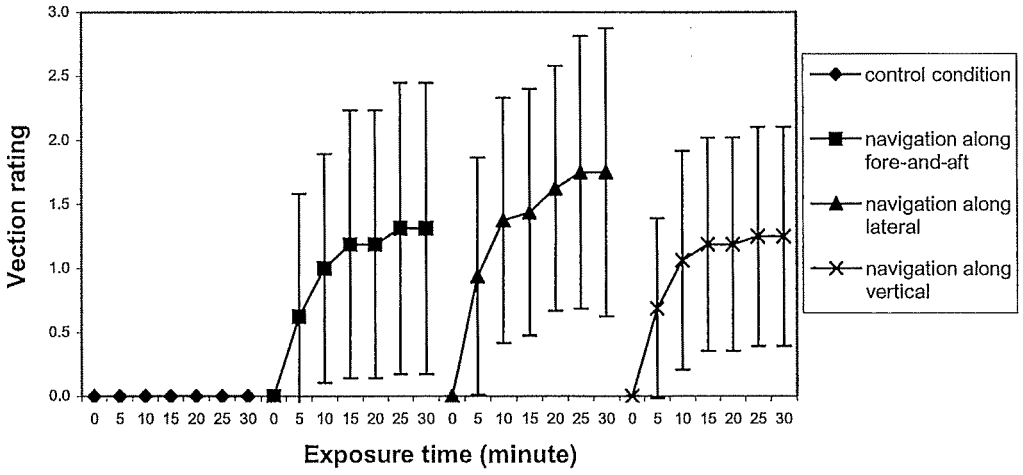

Figure 3.4 Mean vection ratings with standard deviation reported from participants (in Experiment 1a) exposed to VR simulation with stationary scene (control condition) and scene motion in fore-and-aft, lateral and vertical axes. Data are plotted in function of exposure duration. Each data point represents average data of 16 participants.

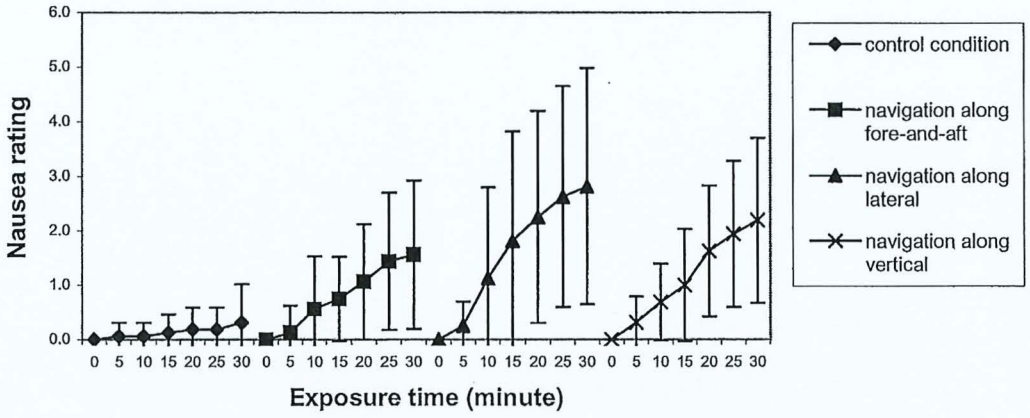

Figure 3.5 Mean nausea ratings with standard deviation reported from participants (in Experiment 1a) exposed to VR simulation with stationary scene (control condition) and scene motion in fore-and-aft, lateral and vertical axes. Data are plotted in function of exposure duration. Each data point represents average data of 16 participants.

Table 3.1 Correlations between nausea ratings and vection ratings within same time interval for a 30 min VR simulation in Experiment 1a

Duration	Correlation coefficient	P value
5 minutes	0.103	P=0.488
10 minutes	0.408	P<0.001
15 minutes	0.540	P<0.001
20 minutes	0.523	P<0.001
25 minutes	0.574	P<0.001
30 minutes	0.635	P<0.001

Table 3.2 Correlations between nausea ratings and vection ratings within same navigation condition for a 30 min VR simulation in Experiment 1a

Condition	Correlation coefficient	P value
Fore-and-aft	0.557	P<0.001
Lateral	0.674	P<0.001
Vertical	0.525	P<0.001

The correlation coefficients shown in the two tables indicated strong linear correlation relationship between vection ratings and nausea ratings in VR simulation. These results were consistent with the hypothesis that linear vection can possibly produce cybersickness in VEs. Two ANOVAs (Analysis of Variance) on vection ratings and nausea ratings were performed to study the effect of navigation conditions, gender and duration. Navigation condition, duration of exposure, gender were all found to have significant effects on vection ratings and nausea ratings ($p<0.05$). Meanwhile, the interaction between navigation condition and gender as well as the interaction between navigation condition and duration of exposure showed significant effects on these two ratings ($p<0.05$).

Table 3.3 ANOVA table on vection ratings analyzing the effects of gender, exposure duration, and navigation conditions for a 30 min VR simulation in Experiment 1a

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Navigation condition	3	100.96	33.65	64.27	<0.01
Gender	1	19.72	19.72	37.67	<0.01
Duration	6	55.78	9.30	17.75	<0.01
Condition*Gender	3	16.96	5.65	10.79	<0.01
Condition*Duration	18	19.72	1.17	2.23	<0.01
Gender*Duration	6	3.65	0.61	1.16	0.33
Condition*Gender*Duration	18	6.92	0.38	0.73	0.78
Error	392	205.25	0.52		
Total	447	430.28			

Table 3.4 ANOVA table on nausea ratings analyzing the effects of gender, exposure duration, and navigation conditions for a 30 min VR simulation in Experiment 1a

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Navigation condition	3	112.19	37.40	31.82	<0.01
Gender	1	8.58	8.58	7.30	0.01
Duration	6	178.37	29.73	25.29	<0.01
Condition*Gender	3	30.79	10.26	8.73	<0.01
Condition*Duration	18	49.47	2.75	2.34	<0.01
Gender*Duration	6	3.45	0.58	0.49	0.82
Condition*Gender*Duration	18	15.17	0.84	0.72	0.80
Error	392	460.75	1.18		
Total	447	858.78			

In order to further investigate the effects of translational navigations, we performed a multiple comparison analysis using the Student-Newman-Kuels tests on vection ratings of the ANOVA results in Table 3.3. SNK results were shown in Table 3.5.

Table 3.5 Student-Newman-Kuels (SNK) tests indicating the effects of (a) navigation conditions, (b) duration, and (c) gender on vection ratings for a 30 min VR simulation in Experiment 1a

(a) SNK groupings on the effects of navigation conditions

SNK Grouping	Vection rating	Number	Condition
A	1.3	112	lateral axis
B	1.0	112	vertical axis
B	0.9	112	fore-and-aft axis
C	0.0	112	no motion

(b) SNK groupings on the effects of duration

SNK Grouping	Vection rating	Number	Duration (min)
A	1.1	64	30
A	1.1	64	25
A	1.0	64	20
A	0.9	64	15
A	0.9	64	10
B	0.6	64	5
C	0.0	64	0

(c) SNK groupings on the effects of gender

SNK Grouping	Vection rating	Number	Gender
A	1.0	224	female
B	0.6	224	male

Table 3.5a indicated that subjects experienced significant feeling of vection in three navigation conditions, while in no navigation condition subjects never perceived any vection. Further more, subjects experienced more feeling of vection when navigating along lateral axis than along fore-and-aft axis and vertical axis. Subjects did not report significantly difference for vection ratings between fore-and-aft axes and vertical axes. Table 3.5b indicated that during the first 10 minutes, vection increased significantly while after 10 minutes, vection tended to be stable and did not show any significant difference for the rest 20 minutes. Table 3.5c indicated that gender did show significant effect on vection ratings. Female subjects experienced more vection than male subjects.

Since ANOVA table 3.3 indicated the interaction between navigation condition and duration, and the interaction between navigation condition and gender were significant, in order to further investigation, interaction plots were illustrated in Figure 3.6.

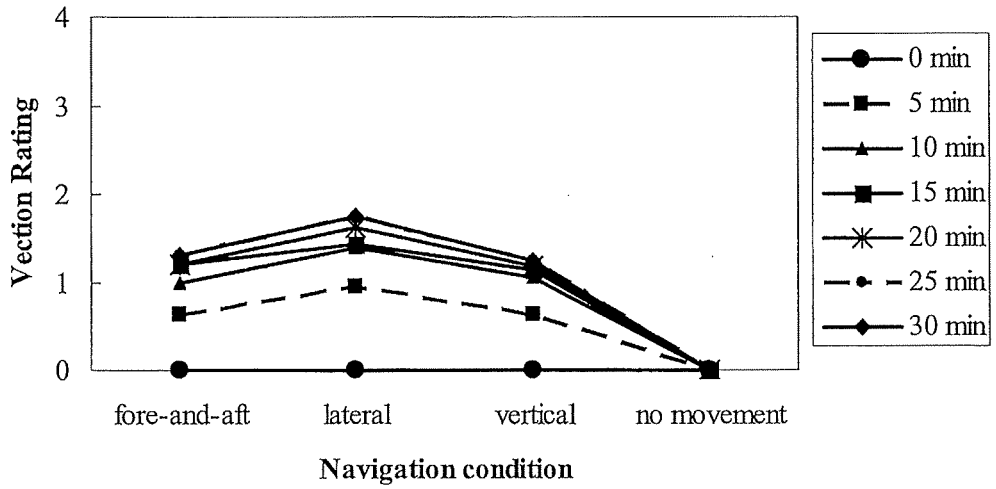

Figure 3.6.a Interaction plot of navigation condition and duration on vection rating in Experiment 1a

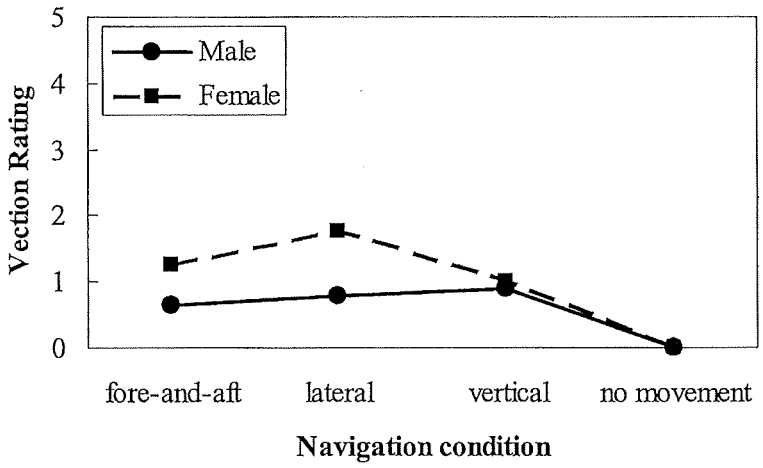

Figure 3.6.b Interaction plot of navigation condition and gender on vection rating in Experiment 1a

Interaction plot 3.6a indicated that at each time duration level, subjects reported higher vection ratings when navigating in lateral compared with other navigation conditions,

moreover, subjects reported zero vection ratings with control condition. The patterns were similar although there were some visibilities. The interaction effects would not affect the main effects found from the ANOVA results.

Interaction plot 3.6b indicated that female subjects reported higher level of vection rating than male subject. However male subject reported similar levels of vection rating among four navigation conditions. This may possibly because female subjects were more sensitive to lateral navigation in VEs. However, this need to be further confirmed in the future study.

Similarly, multiple comparison analysis using Student-Newman-Kuels (SNK) tests on nausea ratings of the ANOVA results in Table 3.4 were shown in Table 3.6.

Table 3.6 Student-Newman-Kuels (SNK) tests indicating the effects of (a) navigation conditions, (b) duration, and (c) gender on nausea ratings for a 30 min VR simulation in Experiment 1a

(a) SNK groupings on the effects of navigation conditions

SNK Grouping	Nausea rating	Number	Condition
A	1.6	112	lateral axis
B	1.1	112	vertical axis
C	0.8	112	fore-and-aft axis
D	0.2	112	no motion

(b) SNK groupings on the effects of duration

SNK Grouping		Nausea rating	Number	Duration (min)
	A	1.8	64	30
B	A	1.6	64	25
B	C	1.3	64	20
D	C	0.9	64	15
D		0.6	64	10
	E	0.2	64	5
	E	0.0	64	0

(c) SNK groupings on the effects of gender

SNK Grouping	Nausea Rating	Number	Gender
A	1.1	224	female
B	0.8	224	male

Table 3.6a indicated that navigations along different axes did have significant effect on nausea ratings. Nausea ratings reported by the subjects without scene motion were significantly lower than those reported by the subjects with virtual navigation. Moreover, the nausea ratings among those three different axes were also significantly different. Subjects scored the highest nausea ratings for lateral axis, then for the vertical axis and scored the lowest rating for the fore-and-aft axis. Considering the results from vection ratings that subjects reported highest vection rating along lateral axes, subjects also reported the severest nausea symptom along lateral axis. It was again consistent with the fact that nausea ratings were highly correlated with vection ratings. Table 3.6b indicated that nausea ratings increased with duration significantly. However, in the absence of navigation, nausea ratings increased at a lower rate with exposure duration compared with navigation condition (Figure 3.5). Table 3.6c indicated that gender had a significant effect on nausea ratings. Females reported higher sickness than males.

The interaction plots between navigation condition and duration, and the interaction between navigation condition and gender were illustrated in Figure 3.7.

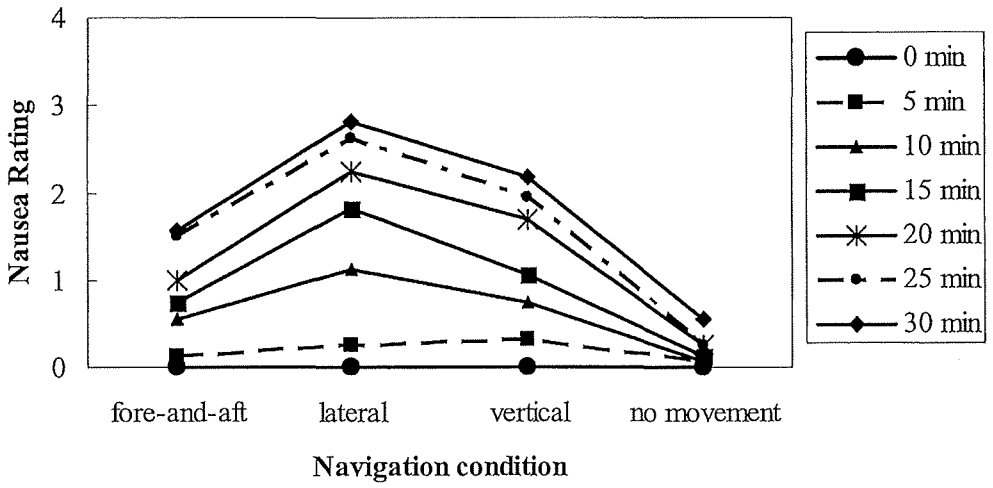

Figure 3.7a Interaction plot of navigation condition and duration on nausea rating in Experiment 1a

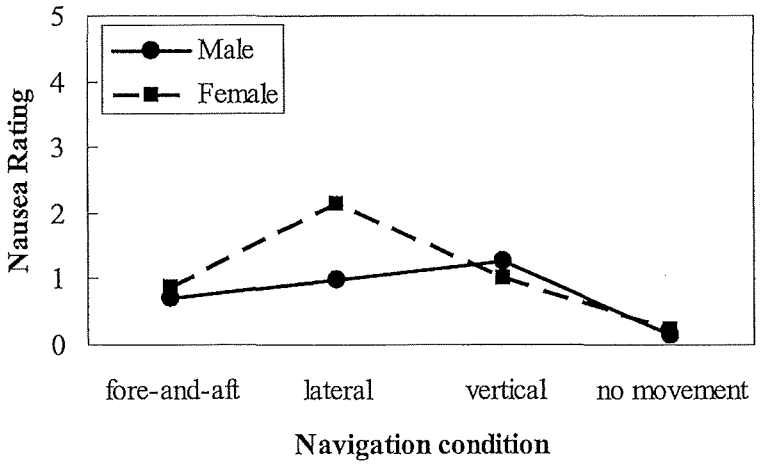

Figure 3.7b Interaction plot of navigation condition and gender on nausea rating in Experiment 1a

Interaction plot 3.7a indicated that basically, at each time duration level, subjects reported higher nausea ratings when navigating in lateral and vertical compared with other navigation conditions; moreover, subjects reported lower nausea ratings with control condition. The patterns were similar although there were some visibilities. The interaction effects would not affect the main effects of navigation condition found from the ANOVA results.

Interaction plot 3.7b indicated that female subjects reported higher level of nausea rating than male subject when navigating in lateral. This may possibly because female subjects were more sensitive to lateral navigation in VEs. Since gender has been found a significant factor in terms of nausea and vection, female subjects were separated from male subjects. The navigation condition and duration effects on the nausea and vection within female subjects and male subjects were investigated. For the male subjects, 2 ANOVAs were performed. Table 3.7 showed the results for nausea rating and vection rating. Similarly, for the female subjects, Table 3.8 showed the ANOVA results for nausea rating and vection rating.

Table 3.7 ANOVA results on vection ratings and nausea ratings analyzing the effects of exposure duration, and navigation conditions for male subjects in a 30 min VR simulation in Experiment 1a

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Vection rating:					
Navigation condition	3	26.91	8.97	16.43	<0.01
Duration	6	15.74	2.62	4.81	<0.01
Condition*Duration	18	6.90	0.38	0.70	0.81
Error	196	107.01	0.55		
Total	223	156.56			
Nausea rating:					
Navigation condition	3	38.58	12.86	13.18	<0.01
Duration	6	67.96	11.32	11.60	<0.01
Condition*Duration	18	19.03	1.05	1.08	0.37
Error	196	191.25	0.98		
Total	223	316.84			

Table 3.8 ANOVA results on vection and nausea rating analyzing the effects of exposure duration, and navigation conditions for female subjects in a 30 min VR simulation in Experiment 1a

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Vection rating:					
Navigation condition	3	91.00	30.33	60.51	<0.01
Duration	6	43.68	7.28	14.53	<0.01
Condition*Duration	18	21.06	1.17	2.33	<0.01
Error	196	98.24	0.50		
Total	223	253.98			
Nausea rating:					
Navigation condition	3	104.39	34.79	25.31	<0.01
Duration	6	113.85	18.97	13.80	<0.01
Condition*Duration	18	45.60	2.53	1.84	0.02
Error	196	269.41	1.37		
Total	223	533.25			

These results indicated that both navigation condition and duration showed significant effects on the nausea rating and vection rating within male or female subjects. However,

the interaction effect between navigation condition and duration was not significant among male subjects for nausea rating or vection rating while it was significant among female subjects both for nausea rating and vection rating. It could be possible that female subjects were more susceptible to motion sickness than male subjects.

3.3.1.2 Simulator Sickness Questionnaire scores

In addition to nausea ratings, participants completed a Simulator Sickness Questionnaire before and after the thirty-minute VR simulation exposure. The four SSQ scores (i.e. nausea subscore, oculomotor subscore, disorientation subscore, and the total sickness score) were calculated according to the formulation in Kennedy and Lane. (1993). Figure 3.8 showed the median and interquartile range (the difference between 75%ile and 25%ile) of four SSQ scores obtained before and after the exposure (since data on SSQ measured in Experiment 1b did not pass normal distribution test, in order to make fair comparison, data were plotted with median and interquartile instead of mean and stand deviation).

Results showed subjects reported higher subscore on disorientation than nausea and oculomotor. These results were quite consistent with the results reported by Kennedy, Stanney and Drexler (1997), Ehrlich and Kolasinsik (1998). It indicated disorientation played an important role in terms of vection-induced cybersickness. Furthermore, subjects reported highest SSQ nausea subscores on the lateral navigation condition followed by vertical navigation and fore-and-aft navigation conditions, which was consistent with the previous results reported in Figure 3.5 found in nausea ratings. For

the SSQ total scores, subjects rated higher score on lateral and vertical navigation conditions than fore-and-aft navigation condition and control condition ($p<0.05$).

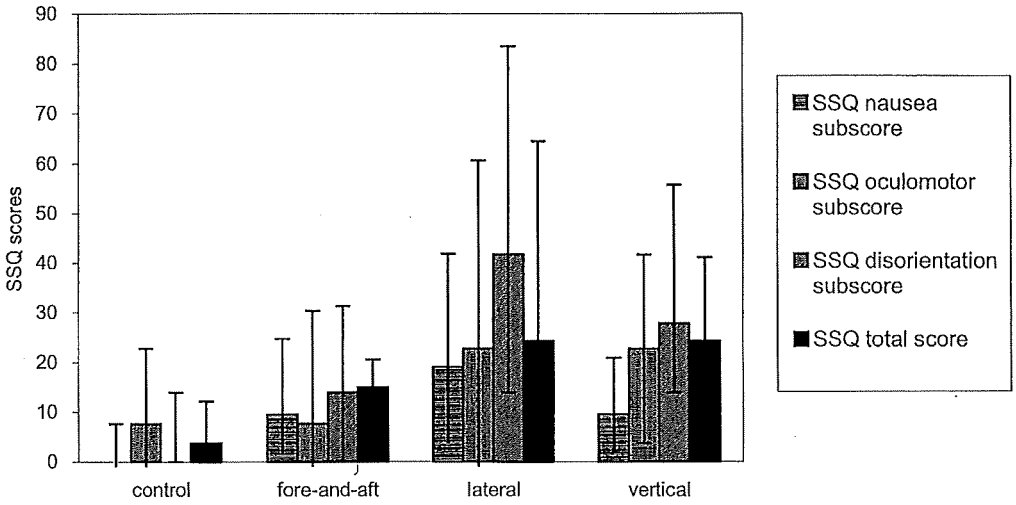

Figure 3.8 Median and interquartile range of simulator sickness scores change (= post sickness scores – pre sickness scores) after 30 minutes simulation reported from participants (in Experiment 1a) exposed to VR simulation with stationary scene (control condition) and scene motion in fore-and-aft, lateral and vertical axes.

Four ANOVAs were conducted to further investigate the effect of navigation condition, gender effects on four increased SSQ scores obtained before and after the exposure. The result indicated that condition and duration showed significant effects on SSQ scores while gender did not.

Table 3.9 ANOVA results on Simulator Sickness Questionnaire (SSQ) nausea scores, orientation scores, oculomotor scores and total scores analyzing the effects of navigation

conditions, exposure duration, and gender after a 30 min VR simulation in the Experiment 1a

a) Dependent variable: Nausea subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Navigation condition	3	5646.99	1882.33	4.56	<0.01
Gender	1	1.42	1.42	0.00	0.95
Navigation condition*Gender	3	1756.24	585.41	1.42	0.25
Error	56	23105.57	412.60		
Total	63	30510.22			

b) Dependent variable: Oculomotor subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Navigation condition	3	6796.91	2265.64	4.54	<0.01
Gender	1	72.72	72.72	0.15	0.70
Navigation condition*Gender	3	390.52	130.17	0.26	0.85
Error	56	27945.36	499.02		
Total	63	35205.51			

c) Dependent variable: Disorientation subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Navigation condition	3	18371.48	6123,83	5.12	<0.01
Gender	1	3499.91	3499.91	2.93	0.09
Navigation condition*Gender	3	1901.33	633.78	0.53	0.66
Error	56	66994.73	1196.33		
Total	63	90767.45			

d) Dependent variable: Total score

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Navigation condition	3	10456.61	3485.54	5.08	<0.01
Gender	1	385.53	385.53	0.56	0.46
Navigation condition*Gender	3	1294.73	431.58	0.63	0.60
Error	56	38406.45	685.83		
Total	63	50543.32			

SNK results on ANOVA showed participants reported significantly higher nausea subscore, disorientation subscores and total scores on lateral navigation and vertical navigation than no navigation condition ($p<0.05$). Subjects reported higher oculomotor subscore on vertical navigation than fore-and-aft navigation and no motion condition ($p<0.05$). Although there was no significant difference among lateral, vertical, fore-and-aft navigation from SNK results, the effect of fore-and-aft navigation and no motion condition was also not significant different. Hence, it is reasonable to believe lateral and vertical navigation produced more sickness level than fore-and-aft navigation. For each subscore as well as for total score, subjects reported almost double sickness level on lateral or vertical navigation than fore-and-aft navigation.

Table 3.10 Student-Newman-Kuels (SNK) tests indicating the effects of navigation conditions on (a) SSQ nausea subscore, (b) SSQ oculomotor subscore, (c) SSQ disorientation subscore and (d) SSQ total score a 30 min VR simulation in Experiment 1a

(a) Dependent variable: Nausea subscore

SNK Grouping		Nausea subscore	Number	Navigation
	A	26.24	16	Lateral
	A	22.06	16	Vertical
B	A	10.73	16	Fore-and-aft
B		2.39	16	No motion

(b) Dependent variable: Oculomotor subscore

SNK Grouping		Oculomotor subscore	Number	Navigation
	A	35.06	16	Vertical
B	A	23.21	16	Lateral
B		14.21	16	Fore-and-aft
B		7.58	16	No motion

(c) Dependent variable: Disorientation subscore

SNK Grouping		Disorientation subscore	Number	Navigation
	A	49.59	16	Lateral
	A	41.76	16	Vertical
B	A	22.62	16	Fore-and-aft
B		6.09	16	No motion

(d) Dependent variable: Total score

SNK Grouping		Total score	Number	Navigation
	A	37.17	16	Vertical
	A	35.06	16	Lateral
B	A	17.30	16	Fore-and-aft
B		6.31	16	No motion

3.1.3 Posture stability tests

Table 3.11 showed the basic statistical description of time holding in the three posture tests: SR, SOPL and SONL. It indicated that the holding time (the time for subject maintained with certain posture) in all the three postures was lower after the VR exposure compared with the holding time before the exposure. However, only the holding time in SR posture was significant different before and after the exposure while for the SOPL and SONL posture, the holding time was not significantly different ($p>0.05$).

Table 3.11 Paired T-test comparing the time of keeping balance before and after the 30 min VR exposure in Experiment 1a

	Pre-exposure		Post-exposure		Pair		t	P
	Mean	SD	Mean	SD	Mean	SD		value
Pair SR: Pre-Post	54.3	10.3	51.4	13.0	2.9	7.8	2.97	<0.01
Pair SOPL: Pre-Post	19.6	7.4	18.4	8.2	1.2	6.7	1.42	0.16
Pair SONL: Pre-Post	18.4	8.5	16.8	8.7	1.6	6.7	1.92	0.06

From the results showed in Table 3.12 using paired T-test to compare the root mean square of head swaying before and after the exposure, no significant results were found on influencing the degree of body swing (as indicated by the root-mean-square movements of the head position in the six directions, i.e., fore-and-aft, lateral, vertical, roll, pitch and yaw) except that along lateral axis for SR test.

Table 3.12 Paired T-test comparing the degree of body swings before and after the 30 min VR exposure in Experiment 1a

Postural Test	Direction	Paired difference	T	P value
SR	Fore-and-aft	-0.17	-0.68	0.50
	Lateral	-0.67	-2.13	0.04
	Vertical	-0.50	-1.66	0.10
	Roll	-0.42	-1.87	0.07
	Pitch	-0.53	-1.85	0.07
	Yaw	-0.63	-1.36	0.18
SOPL	Fore-and-aft	0.08	0.18	0.86
	Lateral	-0.41	-0.97	0.34
	Vertical	0.14	0.25	0.81
	Roll	0.41	1.03	0.31
	Pitch	0.40	0.69	0.49
	Yaw	0.46	0.69	0.49
SONL	Fore-and-aft	0.01	0.35	0.97
	Lateral	-0.28	-1.14	0.26
	Vertical	-0.02	-0.12	0.91
	Roll	0.82	1.47	0.15
	Pitch	0.25	0.61	0.54
	Yaw	0.80	1.55	0.13

3.3.2 Results collected in Experiment 1b

3.3.2.1 Nausea ratings and vection ratings

The mean vection ratings and nausea ratings obtained with the four navigation conditions in Experiment 1b were shown in Figure 3.9 and Figure 3.10. Figure 3.9 indicated vection ratings increased with exposure time for the first 20 minutes while kept stable for the rest 10 minutes. Figure 3.10 indicated that nausea ratings increased with increasing exposure time. Obviously, nausea rating and vection rating showed very similar trend as showed in Figure 3.4 and Figure 3.5 that were reported in the between subject design Experiment 1a. However, the vection rating and nausea rating were not as same severity as in Experiment 1a. The possible reasons and explanation will be discussed in the discussion section of this chapter.

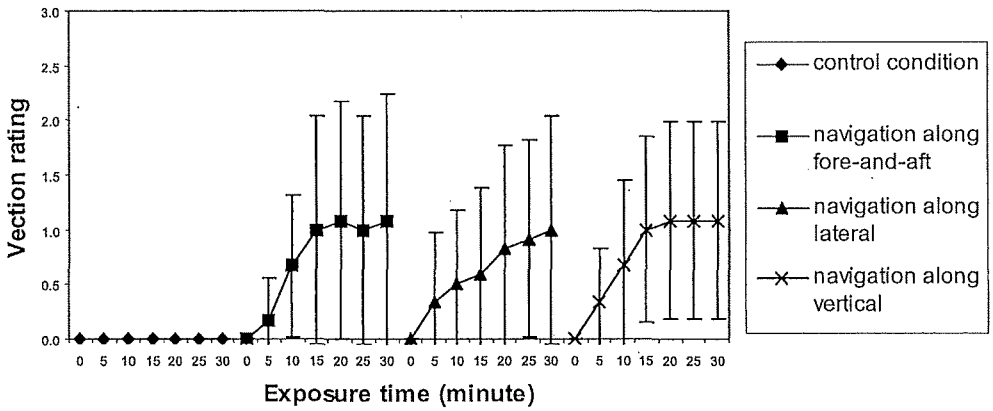

Figure 3.9 Mean vection ratings with standard deviation reported from participants (in Experiment 1b) exposed to VR simulation with stationary scene (control condition) and scene motion in fore-and-aft, lateral and vertical axes. Data are plotted in function of exposure duration. Each data point represents average data of 12 participants.

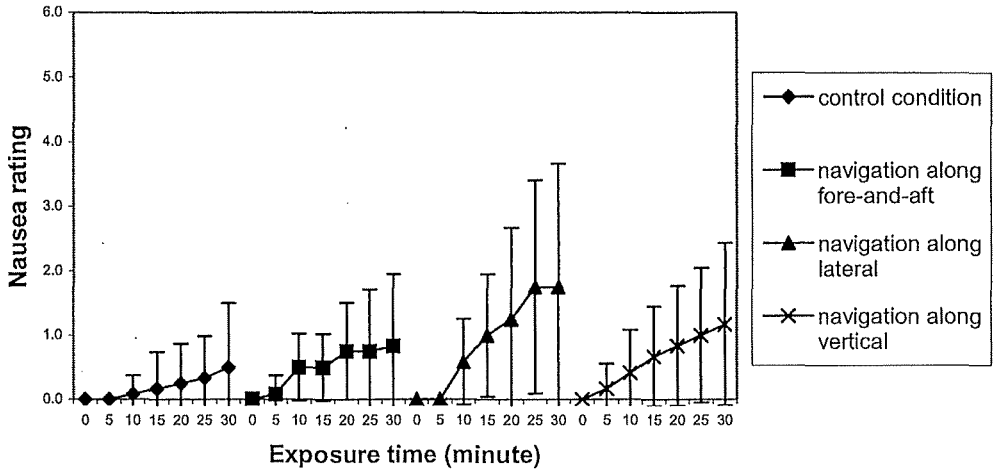

Figure 3.10 Mean nausea ratings with standard deviation reported from participants (in Experiment 1b) exposed to VR simulation with stationary scene (control condition) and scene motion in fore-and-aft, lateral and vertical axes. Data are plotted in function of exposure duration. Each data point represents average data of 12 participants.

Two ANOVAs on vection ratings and nausea ratings were performed to study the effect of participants, navigation condition, gender and duration (Three-way interactions were not calculated due to lack of degrees of freedom in source data). Participants, navigation condition, duration of exposure, gender were found to have significant effects on vection rating and nausea rating ($p<0.05$). Particular, participants reported significant higher nausea ratings and on lateral navigation than the other three conditions ($p<0.05$). These results obtained from Experiment 1b were again very consistent with previous results on nausea ratings and vection ratings obtained from Experiment 1a, except that all the interactions among these factors were not significant in Experiment 1b.

Table 3.13 ANOVA results on vection ratings and nausea ratings analyzing the effects of participants, exposure duration, and navigation conditions in Experiment 1b

Vection Rating Source	DF	F Value	Pr>F
Participants	11	20.08	<0.001
Navigation Condition	3	35.81	<0.001
Duration	6	16.37	<0.001
Gender	1	19.71	<0.001
Error	314		
Total	335		
Nausea Rating Source	**DF**	**F Value**	**Pr>F**
Participants	11	11.07	<0.001
Navigation Condition	3	13.38	<0.001
Duration	6	16.78	<0.001
Gender	1	2.87	0.091
Error	314		
Total	335		

3.3.2.2 Simulation Sickness Questionnaire scores

Figure 3.11 showed the median and interquartile range of four SSQ scores obtained before and after the exposure. In the within-subject design experiment, subjects reported highest both SSQ total score and nausea subscore on the lateral navigation condition.

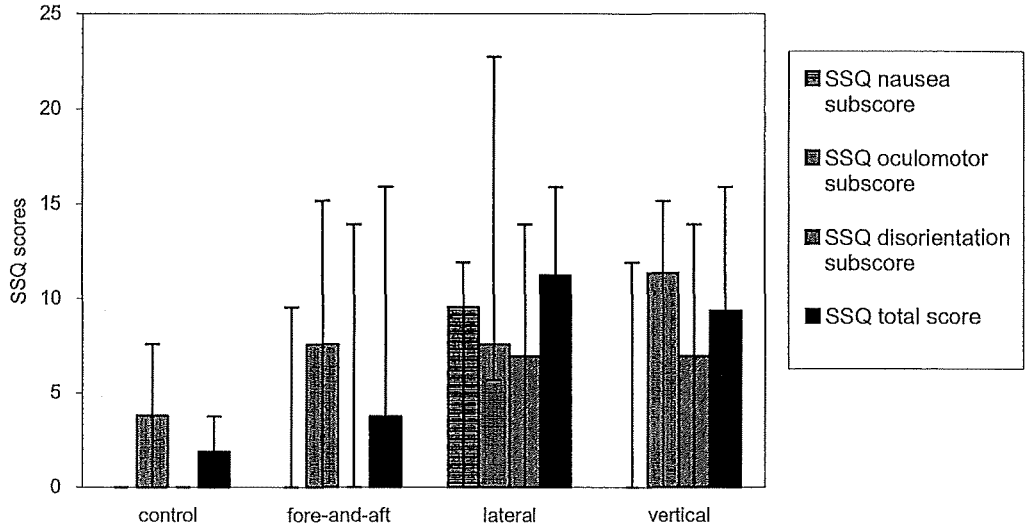

Figure 3.11 The median and interquartile range of simulator sickness scores change (= post sickness scores – pre sickness scores) after 30 minutes simulation reported from participants (in experiment 1b) exposed to VR simulation with stationary scene (control condition) and scene motion in fore-and-aft, lateral and vertical axes

SSQ data obtained from Experiment 1b did not follow normal distribution (checked by kolmogorov-smirnov Test, see Appendix D). Nonparametric statistics method Friedman test was used to test the effect of navigation along different axes on the SSQ scores. Results indicated that navigation along different axes could significantly affect SSQ scores ($p=0.018$). Participants reported highest four SSQ scores on lateral condition.

3.3.2.3 Postural stability tests

Similarly, no significant results for the postural stability tests were found. The possible reason could be due to the large subject variability as well as limited exposure duration.

3.4 Discussion

3.4.1 Effects of navigation along three translational axes

Results obtained from these two experiments indicated that scene movements along the fore-and-aft, lateral and vertical axes in a Virtual Environment were shown to significantly increase the rated level of cybersickness measured by nausea rating ($p<0.01$) compared with control condition which referring to stationary scene movement. For SSQ scores, lateral navigation and vertical navigation significantly produced higher level of sickness than control condition. After 10 minutes exposure, nausea ratings were highly correlated with vection ratings (correlation coefficient >0.5, $p<0.01$). It indicated that visual scene movement could significantly cause the feeling of vection and nausea, moreover, these two feeling could be highly correlated.

From the results of nausea ratings, among the three translational axes, navigation along lateral axis could generate highest nausea level. In Experiment 1a, subjects reported mean nausea rating 2.8 after 30 minutes simulation experiencing lateral vection, while the corresponding mean nausea rating for vertical vection, fore-and-aft vection and no motion were 2.2, 1.6 and 0.3 respectively. Meanwhile, subjects rated higher SSQ total scores while they were experiencing vection along lateral or vertical axes than fore-and-aft axis or control condition. Reported from Experiment 1a, the mean total SSQ score for lateral, vertical, fore-and-aft navigation and control condition were 37, 39, 19 and 8 respectively. The sickness levels between lateral navigation and vertical navigation were

not significantly different. Further SNK analysis indicated that lateral navigation and vertical navigation would generate same amount of sickness level in terms of SSQ total score as well as other three subscores. The possible reason could be due to much more horizontal or vertical eye movement – optokinetic nystagmus occurred during the simulation when subjects experienced lateral or vertical navigations. Hu and Stern (1998) found there existed strong positive relationship between optokinetic nystagmus and the severity of vection-induced motion sickness. Research need to be done to further confirm and verify the relationship between optokinetic nystagmus and the level of cybersickness to find the reason why lateral navigation and vertical navigation would cause higher sickness level in VEs than fore-and-aft navigation.

Another concern on why subjects reported higher sickness level on the condition of scene movement along lateral axis was the yaw head movement made every 75 seconds adopted to encourage the immersion of participants during simulation. It would be possible that when subjects were experiencing lateral vection, physical yaw head movement would increase the subject's disorientation sensation. In order to verify this possible noise, an additional testing experiment was conducted on 8 subjects (4 male and 4 female from 23 to 35 years old). Each subject participated in the navigation condition of scene movement along lateral axis, where the VR simulation was exactly the same as in Experiment 1a except that participants did not turn right or left every 75 seconds during the 30-minute exposure. The mean vection rating, nausea rating and SSQ scores from Experiment 1a for lateral navigation condition and this testing experiment were reported in Table 3.13. A T-test (see Table 3.14) was applied to check whether sickness level under lateral navigation without yaw head movement was different from with yaw

head movement every 75 second. Results indicated that there was not any significant difference between these two conditions which means yaw head movement did not increase sickness level than without yaw head movement ($p>0.05$) in lateral navigation.

Table 3.14(a) Mean nausea ratings and vection ratings reported in with and without yaw head movements every 75 seconds with scene movements along lateral axis.

Duration	Nausea Rating		Vection Rating	
	With yaw head movements	Without yaw head movements	With yaw head movements	Without yaw head movements
5	0.3	0.0	0.9	0.4
10	1.1	0.5	1.4	1.3
15	1.8	1.3	1.4	1.5
20	2.3	1.8	1.6	1.5
25	2.6	2.3	1.8	1.6
30	2.8	2.5	1.8	1.8

(b) Mean SSQ scores reported in with and without yaw head movements every 75 seconds with scene movements along lateral axis.

SSQ Scores	With yaw head Movements	Without yaw head Movements
Nausea Subscore	26.2	20.3
Oculomotor Subscore	26.5	37.9
Disorientation Subscore	49.6	43.5
Total Score	36.7	38.3

Table 3.15 T-test on nausea ratings and vection ratings and SSQ scores reported in with and without yaw head movements every 75 seconds with scene movements along lateral axis.

Measurements	T	P value
Nausea rating at the end of 30 minutes exposure	0.338	0.369
Vection rating at the end of 30 minutes exposure	0.020	0.500
SSQ nausea subscore	-0.634	0.266
SSQ oculomotor subscore	-1.036	0.156
SSQ disorientation subscore	0.331	0.372
SSQ total score	0.127	0.450

3.4.2 Effects of duration

In the presence of scene movement along translational axes, exposure to a Virtual Environment for a period longer than 10 minutes, subjects experienced significant increased level of nausea rating ($p<0.01$). It seemed that the sickness level increases rapidly for the first 10 to 15 minutes, and then the increasing rate slowed down for the rest of duration.

Results also indicated that there existed significant positive correlation between vection ratings and nausea ratings. This finding was also supported by Hettinger and Riccio (1992). Both vection ratings and nausea ratings increased with increasing duration for a certain level, and then kept stable.

3.4.3 Effects of gender

Gender differences were also found in these two experiments, but only found in nausea rating ($p=0.033$ in the between-subject experiment and $p<0.001$ in the within-subject experiment) while it was not found in SSQ total score. Female subjects experienced higher level of vection and nausea than male subjects. The results were quite consistent with previous founding (Kennedy et al., 1995). It is possible that by nature, female subjects are more sensitive to motion sickness.

3.4.4 Correlations between dependent variables

Correlations between nausea ratings, vection ratings, and SSQ scores obtained at the end of 30 min VR simulation in Experiment 1a were shown in Table 3.16. From this table, correlations between vection ratings, nausea ratings and SSQ scores were significantly correlated ($p<0.01$). Hence, the idea of cybersickness is believed as a type of visually induced motion sickness is supported by our study.

Table 3.16 Correlations between nausea ratings, vection ratings, and SSQ scores at the end of 30 min VR simulation in Experiment 1a

		Nausea Rating	Vection Rating	SSQ_NS	SSQ_OS	SSQ_DS	SSQ_TS
Nausea Rating	Pearson Correlation	1.00	0.72**	0.837**	0.64**	0.775**	0.79**
	Sig.		<0.01	<0.01	<0.01	<0.01	<0.01
Vection Rating	Pearson Correlation		1.00	0.56**	0.52**	0.60**	0.60**
	Sig.			<0.01	<0.01	<0.01	<0.01
SSQ_NS	Pearson Correlation			1.00	0.77**	0.76**	0.90**
	Sig.				<0.01	<0.01	<0.01
SSQ_OS	Pearson Correlation				1.00	0.83**	0.95**
	Sig.					<0.01	<0.01
SSQ_DS	Pearson Correlation					1.00	0.94**
	Sig.						<0.01
SSQ_TS	Pearson Correlation						1.00
	Sig.						

** Correlation is significant at the 0.01 level

3.4.5 Comparing results from the between-subject experiment and the within-subject experiment

From results of the between-subject experiment and the within-subject experiment, it seemed that the effects of translational navigations along three different axes on cybersickness were quite consistent which indicated good experimental repeatability. However, participants in the within-subject design experiment reported low level of average sickness compared with that obtained from the between-subject experiment. One possible reason would be the choice of subjects. Since the twelve subjects who participated in all the four navigation conditions also were parts of subjects in the between-subject design experiment, it was interesting to further look at these twelve subjects' profile by comparing with other subjects in the between-subject design

experiment. From Table 3.17, obviously, the subjects who participated in all the four navigation conditions were generally less sensitive to motion sickness associated with VR simulation. Ten out of twelve subjects got sickness level lower than the corresponding average sickness level within the same navigation condition. Only two of twelve rated high sickness level than the average level. Therefore, in some sense, there existed bias on the results of the within-subject design experiment, and the average sickness level may be underestimated due to the choice of the subjects, although the primary effects of translational navigation on cybersickness were still consistent with the between-subject design experiment. However, it was reasonable and justifiable that subjects who were more susceptible to cybersickness were not willing to be exposed in VR simulations for four times.

Table 3.17 SSQ total scores for subjects participating in the within-subject experiment in the first period and with corresponding rank. 1/16 ------lowest score among 16 data points; 16/16 ------ highest score among 16 data points.

Subject	SSQ total score during first period	Rank	Corresponding Group Average SSQ total score
1	3.7	2/16	38.8
2	0	1/16	38.8
3	18.7	7/16	18.7
4	15.0	3/16	36.7
5	3.7	1/16	36.7
6	18.7	7/16	18.7
7	33.7	6/16	36.7
8	44.9 *	15/16	8.0
9	11.2	3/16	36.7
10	3.7	5/16	8.0
11	18.7	7/16	18.7
12	29.9 *	13/16	18.7

Another possible reason could be the subjects' maintenance and habituation to the VEs. Howarth and Hill (1999) reported that some habituation to the virtual simulation sickness had remained until six months break. The average post-SSQ score total score obtained from 12 subjects in session 1, 2, 3, and 4 (the interval between two sessions is at least four weeks) was 17(Std: 13), 16(Std: 15), 8(Std: 8) and 6(Std: 7). Although, no significant post-SSQ score difference was found among these 4 sessions, a decreasing trend could still be seen.

3.5 Conclusions and implications

This study investigated the effects of scene movements along different translational axes on the level of simulator sickness associated with VR simulation. Two experiments were conducted: one was between-subject design and the other was within-subject design. The latter was conducted for two reasons: (i) verify and validate the results from the between-subject design experiments; (ii) minimize the inter-subject variations. Results obtained from the within-subject experiment showed similar trends and patterns compared with those from the between-subject experiment, which meant the results were consistent and repeatable. However, due to the issues addressed in 3.4, conclusions drawn in followings were based on the results obtained in the between-subject design experiment.

Our results indicated that scene movements in all three translational axes (i.e., fore-and-aft, lateral and vertical) can significantly increase the level of cybersickness measured by

nausea and Simulator Sickness Questionnaire (SSQ) scores than without scene movements. In the presence of virtual navigation along translational axes, exposure to a Virtual Environment for a period longer than 10 minutes, subjects reported significant increased level of nausea rating ($p<0.01$). The sickness level increases rapidly for the first 10 to 15 minutes, and then the increasing rate was less for the rest of exposure. In the meanwhile, there existed strong correlation relationships between vection ratings and nausea ratings which supported the hypothesis that cybersickness is a type of vection-induced motion sickness.

Essentially, this study also found that the effects of translational navigations in VE on cybersickness among three different axes were significantly different. The level of nausea rating associated with scene movements in the lateral axis was the highest followed by vertical axis and fore-and-aft axis ($p<0.01$). Subjects reported significantly higher SSQ total score on lateral navigation and vertical navigation than no motion condition ($p<0.05$) while there was no significant difference between fore-and-aft navigation and no motion condition. Hence, it is believed that virtually navigating along lateral or vertical in VE may contribute to more symptom of sickness than along fore-and-aft or no navigation.

Surprisingly, no significant effects of translational navigation in VEs were found on postural stability yet. The reason could be due to not enough exposure duration in our experiments. Hence, the postural stability tests before and after the VR exposure need to be further studied in the future.

As reviewed in the literature review, many studies have reported and confirmed that visual scene movements can play an important role in producing simulator sickness in VEs. In order to study the cause of cybersickness as well as to predict the cybersickness associated with VR simulations, the investigations on the effects of scene movement in different translational axes are necessary. The results found from this study linking with another peer study (Lo and So, 2001) contributed to provide a systematic way to partially predict cybersickness based on the investigation on scene movements in a Virtual Environment. In other words, if the scene movements in a Virtual Environment can be measured and quantified along different axes, then visual scene movement along single axis may become an independent variable and contribute to predicting the responding cybersickness level associated with VR simulation. Navigation axes should be considered in the prediction formula. The effects of translational and rotational navigations on cybersickness are critical to the prediction formula since they provide the profile of relative impact of navigation axes.

A series of experiments need to be conducted to further investigate the effects of navigation velocities in different motion axes, where the level of navigation velocities will be manipulated. We choose three axes to further study because of the following reasons:

1. From this study, it implies lateral navigation and vertical navigation in VEs generally may produce more sickness among users compare with fore-and-aft navigation. We need to further study lateral or vertical navigation. As subjects reported highest nausea rating associated with scene movements in the lateral axis followed by vertical axis and fore-

and-aft axis ($p<0.01$). Moreover, subjects also experienced highest vection feeling when they were navigating in lateral ($p<0.01$). Therefore, we believe it makes sense to choose lateral navigation as a representative between lateral navigation and vertical navigation to be further studied.

2. The previous study indicated by using sine-wave scene movement oscillation in VEs at r.m.s 30deg/sec in yaw, pitch and roll didn't show significant different effects on level of cybersickness. We aim to further investigate the effects of different levels navigation velocities in rotational axis. Since this is the first step towards further investigation, among three rotational axes, we choose yaw as a representative. In the research study of visually induced motion sickness, rotating drum in yaw is usually used (Hu et al. 1989; Hu et al., 1997; Kennedy, 1996). By studying yaw scene movements in different navigation velocities, we can make some meaningful comparisons, especially with the study conducted by Hu et al. in 1989 where a experiment on investigation of visually induced motion sickness as a function of speed of rotating drum (in yaw axis) was reported.

3. The effects of the navigation velocity in fore-and-aft axis will be further studied by extending the scope of navigation velocities. Moreover, we will change the virtual environment compare with a previous study (So et al., 2001b). By repeating the investigation on the effects of navigation velocity in fore-and-aft axis, we can also exam the general validity of the results obtained.

Chapter 4 Effects of navigation velocities in fore-and-aft on level of cybersickness: repeat and extension (Experiment 2)

4.1 Objectives

The objective of this experiment is to investigate the effects of different levels of navigation velocities in fore-and-aft on the level of cybersickness. To compare with a previous experiment from So et al. (2001b) which used eight levels of navigation velocities in fore-and-aft in a metropolitan city Virtual Environment, having an root mean squares (r.m.s.) navigation velocity range from 3m/sec to 60m/sec, another virtual environment with an indoor room scenery was built. Moreover, the range of r.m.s navigation velocities in fore-and-aft were extended. The six level of r.m.s. navigation velocities in fore-and-aft were used in this experiment: 3m/sec, 8m/sec, 15m/sec, 30m/sec, 60m/sec and 150m/sec. In general, two main objectives will be achieved by conducting this experiment. Firstly, we changed the virtual environment, by repeating the investigation on the effects of navigation velocity in fore-and-aft axis, we can examine the general validity of the results obtained; Secondly, the effects of the navigation velocity in fore-and-aft axis were further studied by extending the scope of navigation velocities.

Moreover, in So et al.'s study, the navigation movements are dominantly in the fore-and-aft. However, it did contain motion in other axes including a few movements in yaw, pitch, roll, lateral and vertical. Therefore, strictly speaking, Experiment 2 is the

first experiment that has isolated the effects of navigation velocity in fore-and-aft axis.

4.2 Methodology

4.2.1 Participants

Twenty four male Chinese and twenty four female Chinese university students and staff between 19 and 30 years of age participated in this experiment. Each of them was paid HK$50 as compensation for his/her time. All participants were consented volunteers who were healthy and free of medication and illness. The Human Subject and Research Ethics Committee at the Hong Kong University of Science and Technology approved the experiment.

4.2.2 Apparatus and Virtual Reality Simulations

The virtual scene was constructed using a Virtual Reality authoring software (World Tool Kit, Release 9) running on a Silicon Graphics Onyx II (Silicon Graphics, Inc.) workstation. The program was written in C++ language. The VE was presented on a V8 (Virtual Research Systems, Inc.) LCD Head-Mounted Display (HMD) with a field-of-view of 48 degree in horizontal and 36 degree in vertical. The images were presented on the HMD in binocular mode. A Polhemus 3-Space magnetic tracker (Polhemus, Inc.) was used to measure the head position and orientation at a rate of 30/sec during the VR simulation. The apparatus used in this experiment is shown in Figure 4.1.

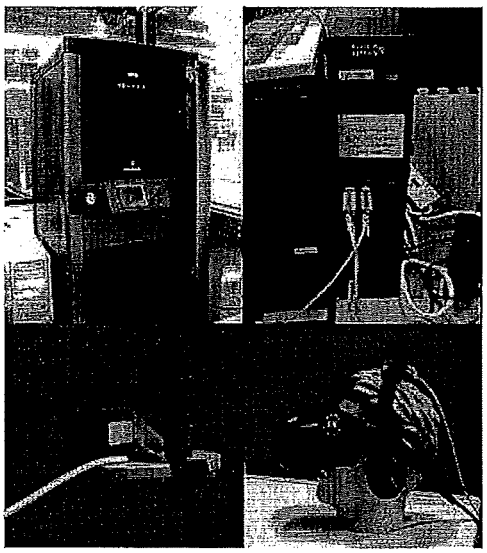

Figure 4.1 Apparatus used in Experiment 2

The virtual environment consisted of a large room with 40m in length, 40m in width and 40m in height (as described in chapter 3, sample snapshots were given in figure 4.2). All participants were exposed to the same VE, but each group of 8 participants virtually navigated inside the room in fore-and-aft at one of six different r.m.s navigation velocities: 3m/sec, 8m/sec, 15m/sec, 30m/sec, 60m/sec and 150m/sec. The navigation path was presented in sinusoidal wave movements, in which the amplitude was 18m. The calculation of the standard sinusoidal wave was as below:

$$Displacement = ASin2\pi ft$$

with six frequencies used in the experiment,

$$f_1 = 0.0375hz$$

$$f_2 = 0.1hz$$

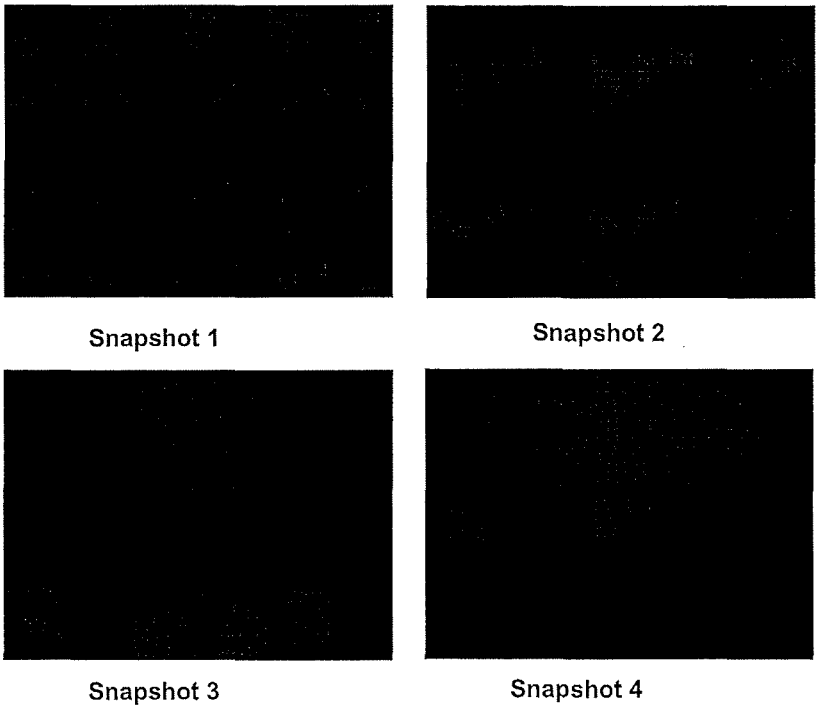

Figure 4.2 Four sample snapshots of the virtual environment used in Experiment 2

$$f_3 = 0.1875hz$$

$$f_4 = 0.375hz$$

$$f_5 = 0.75hz$$

$$f_6 = 1.875hz$$

$r.m.s.velocity = \sqrt{2}\pi ftA \quad where, A = 18m$

i.e.,

$r.m.s.V_1 = \sqrt{2} * \pi * 0.0375 * 18 = 3m/\sec$

$r.m.s.V_2 = \sqrt{2} * \pi * 0.1 * 18 = 8m/\sec$

$r.m.s.V_3 = \sqrt{2} * \pi * 0.1875 * 18 = 15m/\sec$

$r.m.s.V_4 = \sqrt{2} * \pi * 0.375 * 18 = 30m/\sec$

$r.m.s.V_5 = \sqrt{2} * \pi * 0.75 * 18 = 60m/\sec$

$r.m.s.V_6 = \sqrt{2} * \pi * 1.875 * 18 = 150m/\sec$

The average frame were 30 frame/second in all the six simulation conditions.

4.2.3 Experimental design

Navigation velocities of 3m/sec, 8m/sec, 15m/sec, 30m/sec,60m/sec and 150m/sec root mean square (r.m.s) in the fore-and-aft axis were investigated. In the meanwhile, gender difference was also considered. Experiment 2 was a full factorial between-subject design experiment. Totally 48 (24 male and 24 female) participants took part in the experiment, and each participant was randomly assigned to one navigation condition. Each condition was tested on 8 subjects (4 male and 4 female). The duration of exposure to the VE took 30 minutes.

4.2.4 Procedures and Measurements

Once participants came in, participants were asked to read and sign a consent form. And then participants were required to complete a Motion Sickness Susceptibility Survey (MSSS, see Appendix F). The subjects' susceptibilities to motion sickness were recorded and measured. These information were used to balance subjects' susceptibilities among different navigation conditions to avoid that, in one particular condition, subjects were biased to have more or less susceptibilities on motion sickness than those in other conditions. Then the participants were randomly assigned to one of the experimental condition. A short training session was given to each participant. During the training session, participants were educated to distinguish vection from

perceived speed of the surround scene and they were reminded to rate only the level of vection, i.e., illusion of self motion. Besides that, they were also educated with the terminologies involved in SSQ, particular, the differences among nausea, dizziness, eyestrain and vertigo as we found participants could possibly get confused with these terminologies based on past experience.

Then, participants were then asked to complete a pre-exposure SSQ. All participants with a pre-exposure SSQ of more than 2 slight symptoms or a pre-exposure SSQ total score of more than 10 were asked to take a rest for 5-10 minutes with their eyes closed. After that, the participants were asked to fill in another pre-exposure SSQ. If the pre-exposure SSQ total score was less than 10, then the experiment proceeded. However, if the pre-exposure SSQ total score was still more than 10, then the participants were asked to come back for another date. Then 30 minutes Virtual Reality simulation was given. During the 30 minutes exposure, participants were asked to keep sitting in an up-right posture. At five-minute intervals, participants were asked to rate verbally their symptoms of nausea on a seven-point scale (Appendix A) and at ten-minute intervals, they were asked to rate their sensation of vection on a 4-point scale (Appendix C). Vection duration was also recorded by pressing a button when the participant experienced vection sensation; meanwhile, if the participant didn't have vection feeling, he/she released the button. Participants head tracking history (in six directions) were also recorded during 30 minutes exposure. In order to encourage participants to be more involved in the VE, from time to time, there were some additional pop-up objects, e.g. cross, circle and cubes with letters, suddenly appeared in front of the participants in the

environment. Participants were asked to speak out and describe what they had seen to the experimenter.

After the exposure of VR simulation, participants were asked to complete a post-exposure SSQ. In addition, during the simulation, if a participant reported the nausea rating of 6 (that is *moderate nausea, want to stop*), then the VR simulation was terminated and the participant was asked to complete the post-exposure SSQ. A score of 6 was assigned for the remaining verbal rating reports.

4.3 Results

Data on nausea ratings, vection ratings, SSQ measurements obtained in Experiment 2 passed the test for normal distribution (See Appendix D.3). Therefore, parametric statistical analysis was applied for the normal distribution data. SAS 8.01 and SPSS 11.0 were adopted to analyze the data collected in this experiment.

4.3.1 Nausea ratings

The mean of nausea ratings reported from participants exposed to VR simulation with different navigation velocities in fore-and-aft were shown in Figure 4.3. Inspection on this figure showed that as the exposure duration increased, nausea rating increased. Moreover, the increasing rate was higher at 30m/sec than those at other velocities. Table 4.1 showed the ANOVA test results of the effects of navigation velocity, exposure duration and gender. Navigation velocity and exposure duration were found significantly

affecting the nausea ratings ($p<0.05$). Gender didn't significantly affect the nausea ratings, while the interaction effects were also not significantly different. Results of Student-Newman-Keuls (SNK) tests shown in Table 4.2 indicated that nausea rating increased significantly after 5 minutes of VR exposure up to around 25 minutes. In the meanwhile, Table 4.2 also indicated that nausea rating increased significantly with increasing navigation velocity from 3m/sec to 30m/sec, after that nausea rating significantly decreased at 60m/sec and became statistically the same with navigation velocity at 150m/sec. The pattern found from this experiment is similar with the previous study (i.e., So et. al, 2001b) and will be further discussed in the discussion section.

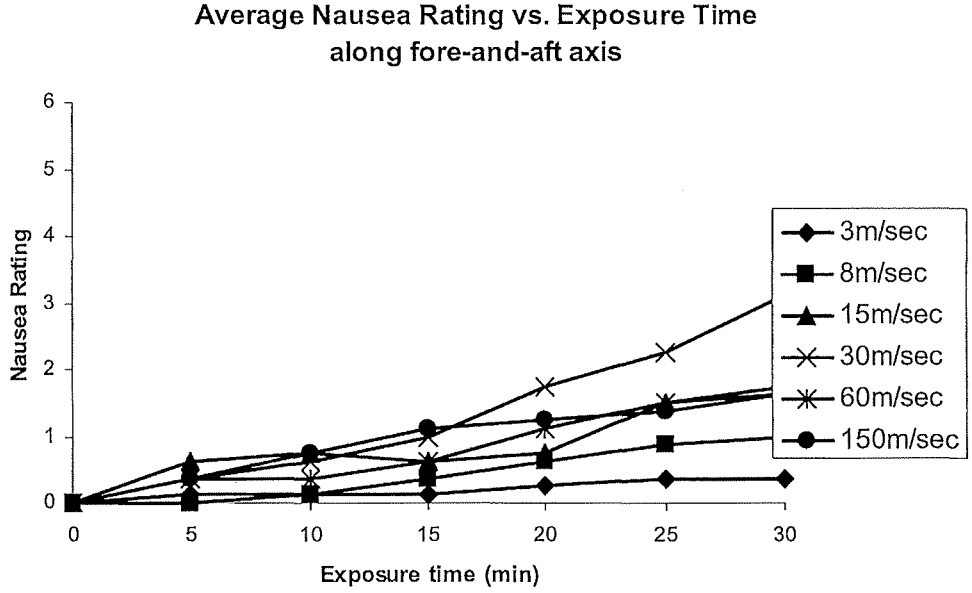

Figure 4.3 The mean of nausea ratings reported from participants exposed to VR simulation with different navigation velocities in fore-and-aft. Data are plotted in function of exposure duration. Each data point represents average data of 8 participants.

Table 4.1 ANOVA table on nausea ratings analyzing the effects of navigation velocity in fore-and-aft, exposure duration, and gender for a 30-min VR simulation in Experiment 2.

	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	5	51.29	10.26	11.5	<0.01
Gender	1	0.01	0.01	0.01	0.91
Duration	6	81.35	13.56	15.22	<0.01
Velocity*Gender	5	7.52	1.5	1.69	0.14
Velocity*Duration	30	28.00	0.93	1.05	0.40
Gender*Duration	6	4.36	0.73	0.82	0.56
Velocity*Gender*Duration	30	10.85	0.36	0.41	1.00
Error	252	224.5	0.89		
Total	335	407.89			

Table 4.2 Student-Newman-Kuels (SNK) tests indicating the effects of (a) navigation velocity (b) duration on nausea ratings for a 30 min VR simulation in Experiment 2.

(a) SNK groupings on the effects of navigation velocity

SNK Grouping	Nausea Rating	Number	Velocity
A	1.32	56	30m/sec
B	0.93	56	150m/sec
B	0.86	56	15m/sec
B	0.80	56	60m/sec
C	0.36	56	8m/sec
C	0.13	56	3m/sec

(b) SNK groupings on the effects of exposure duration

SNK Grouping		Nausea Rating	Number	Duration
	A	1.52	48	30
B	A	1.25	48	25
B	C	0.92	48	20
D	C	0.63	48	15
D	C	0.48	48	10
D	E	0.33	48	5
	E	0.00	48	0

Figure 4.4 illustrate the mean of nausea ratings with standard deviation reported from participants at the end of 30-min VR simulation with different navigation velocities in fore-and-aft. This figure showed the trend of nausea rating as varied with the different navigation velocities in fore-and-aft axis at the end of 30-min VR simulation exposure. It reveals that there exists nonlinear relationship between navigation velocity in fore-and-aft axis and the level of cybersickness.

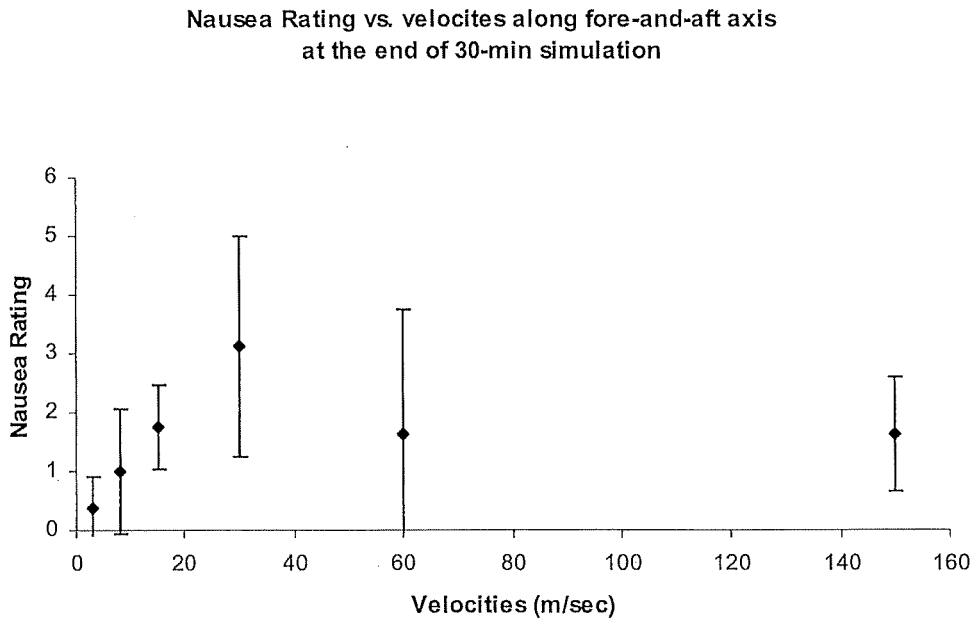

Figure 4.4 The mean of nausea ratings with standard deviation reported from participants at the end of 30-min VR simulation with different navigation velocities in fore-and-aft. Data are plotted in function of velocities. Each data point represents average data of 8 participants.

4.3.2 Vection rating and vection duration

The mean of vection ratings reported from participants exposed to VR simulation with different navigation velocities in fore-and-aft were shown in Figure 4.5. Inspection on this figure showed that vection rating increased for the first 10 minutes, after that, the vection ratings leveled off with increasing exposure duration up to the end of exposure. Table 4.3 showed the ANOVA test results of the effects of navigation velocity, exposure duration and gender on vection ratings. Exposure duration and navigation velocity were found significantly affecting the vection ratings ($p<0.05$). Student-Newman-Keuls test results shown in Table 4.3 indicated that navigation in VE could significantly cause vection feeling, however, vection ratings were not significantly different among 10, 20 or 30 minutes exposure. In the meanwhile, Table 4.3 also indicated that vection ratings were significantly higher when navigation velocity was 60m/sec, among other 5 levels, vection ratings were not significantly different.

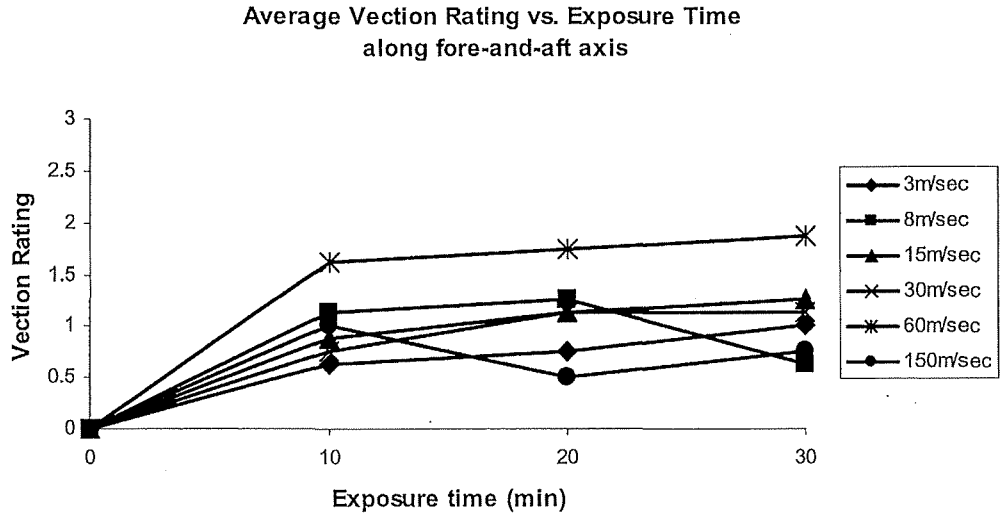

Figure 4.5 The mean of vection ratings reported from participants exposed to VR simulation with different navigation velocities in fore-and-aft. Data are plotted in function of exposure duration. Each data point represents average data of 8 participants.

Table 4.3 ANOVA table on vection ratings analyzing the effects of navigation velocity , exposure duration, and gender for a 30 min VR simulation in Experiment 2

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	5	11.73	2.35	4.26	0.001
Gender	1	1.17	1.17	0.01	0.147
Duration	3	40.93	13.64	24.79	<0.001
Velocity*Gender	5	4.86	0.97	1.77	0.123
Velocity*Duration	15	8.54	0.57	1.03	0.424
Gender*Duration	3	0.43	0.14	0.26	0.852
Velocity*Gender*Duration	15	4.16	0.28	0.50	0.935
Error	144	79.25	0.55		
Total	191	151.08			

Table 4.4 Student-Newman-Kuels (SNK) tests indicating the effects of (a) navigation velocity (b) duration on vection ratings for a 30 min VR simulation in Experiment 2

(a) SNK groupings on the effects of navigation velocity

SNK Grouping	Vection Rating	Number	Velocity
A	1.31	32	60m/sec
B	0.81	32	15m/sec
B	0.75	32	8m/sec
B	0.75	32	30m/sec
B	0.59	32	3m/sec
B	0.56	32	150m/sec

(b) SNK groupings on the effects of exposure duration

SNK Grouping	Vection Rating	Number	Duration
A	1.10	48	30min
A	1.08	48	20min
A	1.00	48	10min
B	0.00	48	0min

As we also use a button to measure the vection duration during the whole VR simulations. Vection duration is defined as, during the whole VR exposure, for how much percentage time, participants had the vection feeling. Figure 4.6 showed the average vection duration as a function of 6 levels of navigation velocities. It showed a partially similar trend as showed in Figure 4.4 that vection duration is increased with navigation velocity up to 30m/sec, after that vection duration decreased. Table 4.4

showed the ANOVA test results of the effects of navigation velocity and gender on vection duration. Student-Newman-Keuls test results shown in Table 4.5 indicated that subjects reported significantly more vection duration with navigation velocity at 30m/sec (with average vection duration of 52.27%) than 3m/sec (with average vection duration of 6.88%). It should be noted that subjects reported highest percentage of vection duration at 30m/sec, which was consistent with the fact that subjects reported highest nausea ratings at 30m/sec; moreover, subjects reported lowest percentage of vection duration at 3m/sec, while subjects reported lowest nausea ratings at 3m/sec.

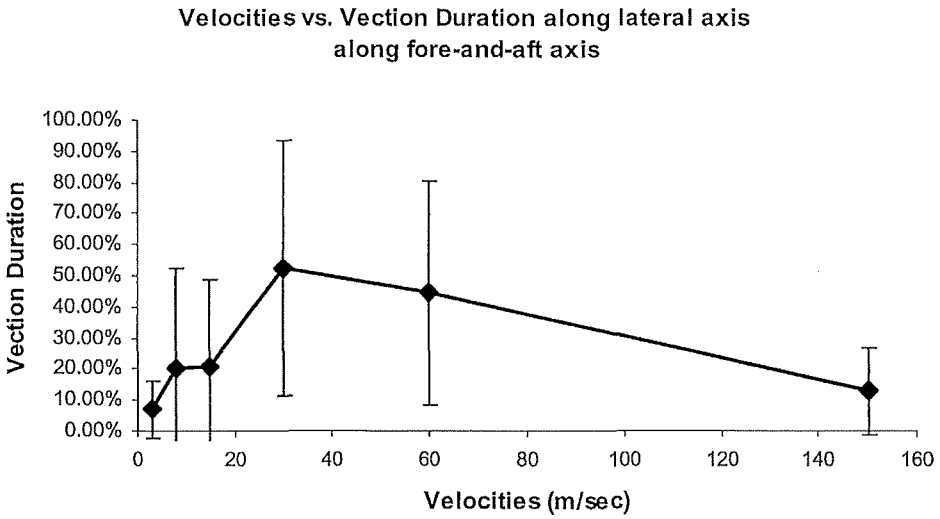

Figure 4.6 The mean of vection duration with standard deviation reported from participants during 30-min VR simulation with different navigation velocities in fore-and-aft. Data are plotted in function of velocities. Each data point represents average data of 8 participants.

Table 4.5 ANOVA table on vection duration analyzing the effects of gender, and navigation velocities for a 30 min VR simulation in Experiment 2

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	5	1.28	0.27	3.48	0.01
Gender	1	0.09	0.09	1.17	0.287
Velocity*Gender	5	0.72	0.14	1.96	0.109
Error	35	2.57	0.07		
Total	46	4.66			

Table 4.6 Student-Newman-Kuels (SNK) tests indicating the effects of navigation velocity on vection duration of a 30 min VR simulation in Experiment 2

SNK Grouping		Vection Duration	Number	Velocity
	A	52.27%	8	30m/sec
B	A	44.41%	7	60m/sec
B	A	21.01%	8	15m/sec
B	A	20.36%	8	8m/sec
B	A	12.90%	8	150m/sec
B		6.88%	8	3m/sec

4.3.3 Simulator Sickness Questionnaire scores

Figure 4.7 showed the change of SSQ scores (Nausea subscore, oculomotor subscore, disorientation subscore and total score) with respect to the navigation velocities in fore-and-aft axis. The change of SSQ score is defined as the difference between post-exposure SSQ score and pre-exposure SSQ score. From this figure, we can see a

trend that SSQ scores increased with increasing navigation velocities up to around 30m/sec, after that the sickness level stabilized. Table 4.7 showed the ANOVA results of the effects of navigation velocity and gender on the four SSQ scores. Gender didn't show significant effect on all the SSQ scores ($p>0.05$). Navigation velocity had significant effects on SSQ nausea score ($p<0.05$). Further SNK results showed that subjects reported significantly higher SSQ nausea scores with navigation velocity at 30m/sec or 60m/sec than navigation velocity at 3m/sec. This pattern was consistent with what was found on nausea rating that subjects also reported significant higher nausea rating when they were navigating at 30m/sec in VEs. Figure 4.8 showed the mean of increased SSQ nausea subscore with standard deviation reported from participants after exposure of 30-min VR simulation with different navigation velocities in fore-and-aft. However, SSQ total score, disorientation subscore and oculomotor subscore did not show significant difference with navigation velocities increase from 3m/sec to 150m/sec. The possible reason could be that nausea subscore is more sensitive to the factor of navigation velocity since a similar relationship could be found from nausea ratings.

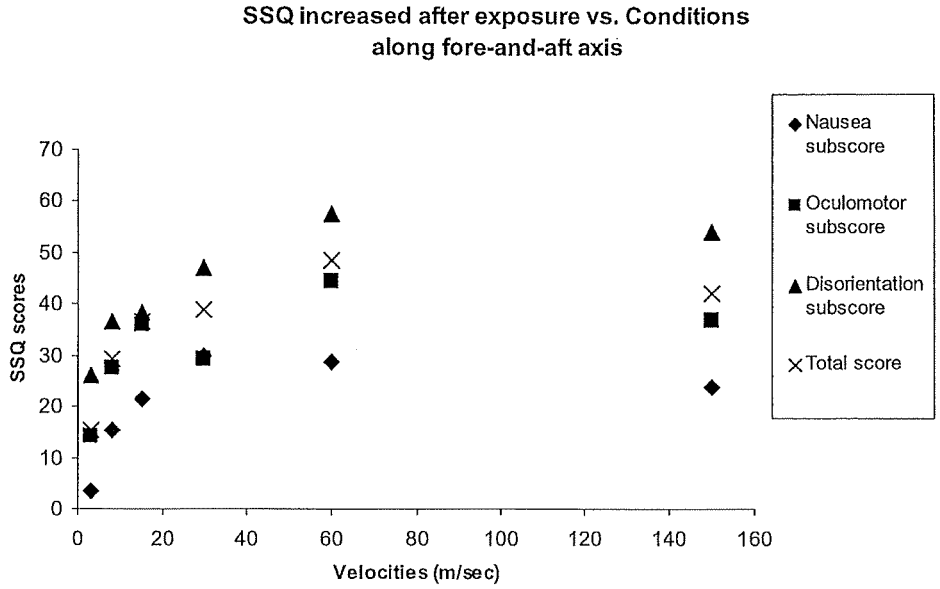

Figure 4.7 The mean of increased SSQ scores reported from participants after exposure of 30-min VR simulation with different navigation velocities in fore-and-aft. Data are plotted in function of velocity. Each data point represents average data of 8 participants.

Table 4.7 ANOVA table on SSQ scores analyzing the effects of gender, and navigation velocities for a 30 min VR simulation in Experiment 2

a) Dependent variable: Nausea subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	5	3809.21	761.84	2.7	0.04
Gender	1	17.06	17.06	0.06	0.81
Velocity*Gender	5	927.18	185.44	0.66	0.66
Error	36	10170.55	282.52		
Total	47	14924.01			

b) Dependent variable: Oculomotor subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	5	4381.05	876.21	1.81	0.14
Gender	1	19.15	19.15	0.04	0.84
Velocity*Gender	5	1905.64	381.13	0.79	0.57
Error	36	17438.02	484.39		
Total	47	23743.86			

c) Dependent variable: Disorientation subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	5	5542.53	1108.51	0.92	0.48
Gender	1	36.33	36.33	0.03	0.86
Velocity*Gender	5	4832.05	966.41	0.80	0.56
Error	36	43548.99	1209.69		
Total	47	53959.91			

d) Dependent variable: Total score

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	5	5371.24	1074.25	1.87	0.12
Gender	1	1.17	1.17	0.01	0.96
Velocity*Gender	5	2380.22	476.04	0.83	0.54
Error	36	20659.69	573.88		
Total	47	28412.31			

Table 4.8 Student-Newman-Kuels (SNK) tests indicating the effects of navigation velocity on nausea subscore of a 30 min VR simulation in Experiment 2

SNK Grouping		Nausea Subscore	Number	Velocity
	A	29.81	8	30m/sec
	A	28.62	8	60m/sec
B	A	23.85	8	150m/sec
B	A	21.47	8	15m/sec
B	A	15.50	8	8m/sec
B		3.58	8	3m/sec

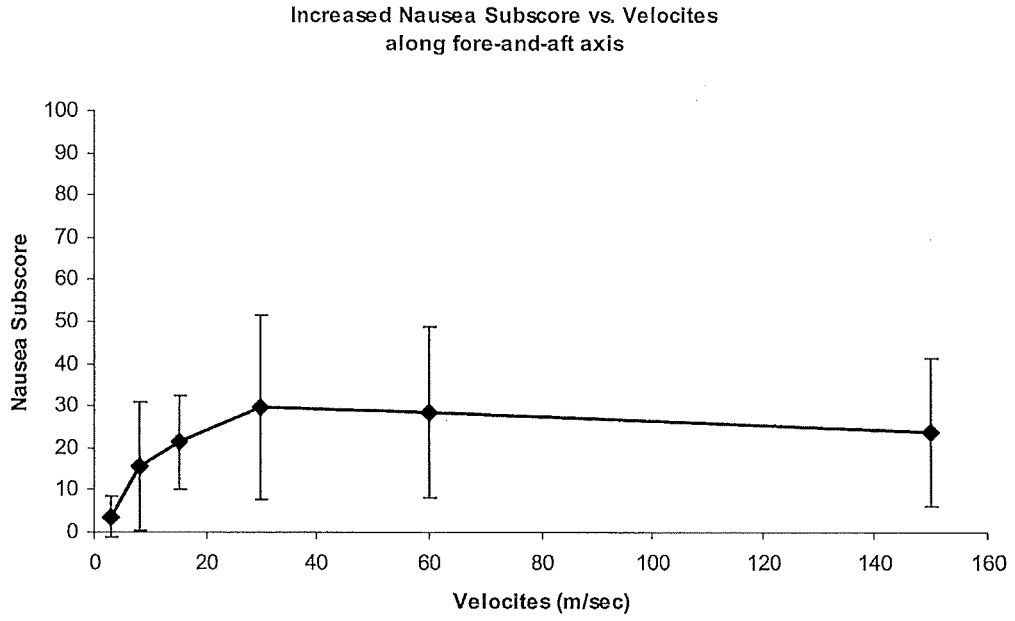

Figure 4.8 The mean of increased SSQ nausea subscore with standard deviation reported from participants after exposure of 30-min VR simulation with different navigation velocities in fore-and-aft. Data are plotted in function of velocity. Each data point represents average data of 8 participants.

4.4 Discussion

4.4.1 Effects of navigation velocity

Results obtained from this experiment indicated that nausea ratings increased with increasing navigation velocity in fore-and-aft axis up to 30m/sec, then nausea ratings significantly decreased at 60m/sec, and became statistically the same at 150m/sec. Subjects reported higher vection rating at 60m/sec than other five experimental conditions. However, subjects didn't report significant different vection ratings among other five conditions. On the contrary, the measurement of percentage of vection duration showed a similar pattern as we found in nausea rating by comparing Figure 4.4 and 4.6. Both figures illustrated nonlinear relationship, i.e., both nausea rating and percentage of vection duration increased when navigation velocity in fore-and-aft increased up to 30m/sec. Beyond 30m/sec, nausea rating and vection duration declined and stabilized. This may indicate that in this experiment, vection duration is a more sensitive indicator to represent the relationship between vection and cybersickness. Consistent with the literature, some studies also used vection duration to represent subject's vection feeling (for example, Flanagan et, al. 2001). More percentage of vection duration could possibly cause severer nausea symptoms.

The change of SSQ scores also implied a partially similar trend we found in the results on nausea rating, although the significant different effect was found only on nausea subscore. Subjects reported significantly higher SSQ nausea subscore at 30m/sec

compared with that at 3m/sec. However, at higher velocities, SSQ nausea subscore didn't significantly decline. It might be due to the measurement of nausea subscore which was more complicated than nausea rating.

Sensory rearrangement theory might account for the finding that different navigation velocities in fore-and-aft in VEs had different effects on the level of cybersickness. The severity of sensory mismatch possibly determined the intensity of nausea symptom. When navigation velocity was lower at 3m/sec, vection was not strong enough to produce a significant mismatch between visual and vestibular system, so that lower level of nausea symptom manifested. However, with the increase in navigation velocities, vection duration became longer and stronger, therefore, nausea symptoms also became stronger. When navigation velocity was 30m/sec, vection feeling reached the highest so that the sensory mismatch was highest. At this level of navigation velocity, subjects reported highest level of cybersickness. When navigation velocities were beyond 30m/sec, vection duration began to drop. It is possible that when scene movements were very fast (30m/sec = 216km/hour), human beings don't have too much experiences of having self motion velocity at such high level in the daily life, therefore, subjects might think the scene is moving rather than themselves are moving.

The nonlinear relationships between navigation velocity in fore-and-aft and sickness levels may also be partially supported by the Steven's power law, which pointed out that the level of sensation is a nonlinear function of the strength of the stimulus. The vection sensation increased nonlinearly with increasing levels of navigation velocity. Vection sensation correlated with cybersickness, therefore sickness level varied nonlinearly with

navigation velocities. Of course, Steven's power law didn't imply the dropped effects when navigation velocity reached a certain level. However, as we have discussed in previous paragraph, when scene movements are very fast, human being may not take it as self motion since it conflict with human past experience.

In conclusion we have demonstrated a nonlinear relationship between navigation velocity in fore-and-aft and levels of cybersickness indicated by nausea rating and SSQ nausea subscores, as well as vection duration.

4.4.2 Effects of duration

Exposure to VR simulation could significantly produce cybersickness ($p<0.01$). Nausea ratings increased significantly with increasing exposure duration up to around 25 minutes. While vection ratings increased for the first 10 minutes, after that, the vection rating became statistically the same with increasing exposure duration. It indicated that vection ratings became saturated after 10 minutes immerse of VR simulation.

4.4.3 Effects of gender

Experiment results showed that gender is not significantly affecting the levels of cybersickness indicated by nausea rating or SSQ scores. Gender also didn't show any significant difference in the results of vection. These results partially disagreed with what was found in Experiment 1a. Possible reasons could be due to the reduced sample size and large subject variability. In Experiment 1a, in each condition, there were 16

participants (8 male and 8 female). However, in Experiment 2, in each condition, there were only 8 participants (4 male and 4 female). We know that large sample size benefits for statistical analysis. This can be treated as a limitation in Experiment 2. From the literature, inconsistent conclusion on the effects of gender were also found (Yoo et al. 1997; Kennedy et al., 1995; Yuen, 2002). It was also possible that human's sensitivity to the VEs could be different. For example, with different VR simulations and different causing factors, the effects of gender on the level of cybersickness may be different.

4.4.4 Correlations between dependent variables

Correlations between nausea ratings, vection ratings, vection duration and SSQ scores obtained at the end of 30 min VR simulation in Experiment 2 were shown in Table 4.9. From this table, patterns of vection duration and vection rating seemed different. Correlations between vection duration and nausea ratings, SSQ scores were not significant; correlation between vection rating and nausea rating was significant; correlation between vection duration and vection rating was significant. On the other hand, nausea rating and SSQ scores were highly correlated ($p<0.01$). The different patterns on vection ratings and vection duration were consistent with a literature by Flanagan et al., 2002.

Table 4.9 Correlations between nausea ratings, vection ratings, vection durations and SSQ scores at the end of 30 min VR simulation in Experiment 2

		Nausea Rating	Vection Rating	Vection Duration	SSQ_NS	SSQ_OS	SSQ_DS	SSQ_TS
Nausea Rating	Pearson Correlation	1.00	0.39**	0.22	0.76**	0.52*	0.53**	0.64**
	Sig.		0.04	0.15	<0.01	0.02	<0.01	<0.01
Vection Rating	Pearson Correlation		1.00	0.65**	-0.06	-0.06	0.18	0.02
	Sig.			<0.01	0.68	0.70	0.23	0.89
Vection Duration	Pearson Correlation			1.00	0.06	-0.02	0.08	0.04
	Sig.				0.69	0.89	0.58	0.81
SSQ_NS	Pearson Correlation				1.00	0.77**	0.67**	0.87**
	Sig.					<0.01	<0.01	<0.01
SSQ_OS	Pearson Correlation					1.00	0.73**	0.94**
	Sig.						<0.01	<0.01
SSQ_DS	Pearson Correlation						1.00	0.89**
	Sig.							<0.01
SSQ_TS	Pearson Correlation							1.00
	Sig.							

**. Correlation is significant at the 0.01 level

4.4.5 Comparing results of the previous study

As we reviewed in chapter 2, a previous study (So et al., 2001b) has been conducted to investigated eight levels of navigation velocities in fore-and-aft. Figure 4.9 illustrated the comparison of effects of different level of navigation velocities on nausea rating of two experiment (this study and a previous study conducted by So et al., 2001b). The corresponding data table related to Figure 4.9 is listed in Table 4.10. Both studies indicated nonlinear effects of navigation velocity. But, the two curves seemed not quite agree, especially the two curves peaked at different horizontal axis. We know that besides navigation velocity, spatial frequency is also an important factor that affects the intensity of the scene movements in VEs. Since in these two experiments, spatial

frequencies are different, in order to make fair comparison, it is beneficial to use spatial velocity (i.e., the product of navigation velocity and spatial frequency) instead of navigation velocity alone to be the manipulating factor. Obviously, Figure 4.10 illustrated a more clear comparison where nausea ratings were displayed as a function of Spatial Velocity in fore-and-aft (corresponding data was listed in Table 4.11). These two curves illustrated roughly similar patterns. There also existed difference between the two studies. In the previous study, when navigation velocity increased to 10m/sec, nausea rating didn't decline, but stabilized. However, in our study, a decline effect was found when navigation velocity increased to a certain level. This actually agreed with a study reported by Hu et al., (1989) that symptoms of vection induced sickness increased, peaked and then declined as the rotating drum speed changed from 15deg/sec to 90deg/sec. By extending the range of navigation velocity, this study provided more complicated understanding of relationships between navigation velocity and levels of cybersickness. Similarly, Figure 4.11 compared the SSQ total scores (corresponding data was listed in Table 4.12) as a function of Spatial Velocity in fore-and-aft in two experiments. The two curves quite agree with each other.

Table 4.10 Average velocity, SF and nausea ratings reported by subjects at the end of 30-min VR simulation of experiment conducted by So et al., 2001b and Experiment 2

No.	VE	R.M.S Velocity (m/sec)	Average SF (cycle/deg)	Nausea rating at the end of 30-min simulation
1	A previous study (So et al., 2001b)	3	0.26	1.75
2	A previous study (So et al., 2001b)	4	0.26	2.20
3	A previous study (So et al., 2001b)	6	0.26	2.10
4	A previous study (So et al., 2001b)	8	0.26	2.17
5	A previous study (So et al., 2001b)	10	0.26	3.55

6	A previous study (So et al., 2001b)	24	0.26	3.25
7	A previous study (So et al., 2001b)	30	0.26	2.67
8	A previous study (So et al., 2001b)	60	0.26	3.33
9	Experiment 2	3	0.10	0.25
10	Experiment 2	8	0.10	0.88
11	Experiment 2	15	0.10	1.75
12	Experiment 2	30	0.10	3.13
13	Experiment 2	60	0.10	1.63
14	Experiment 2	150	0.10	1.63

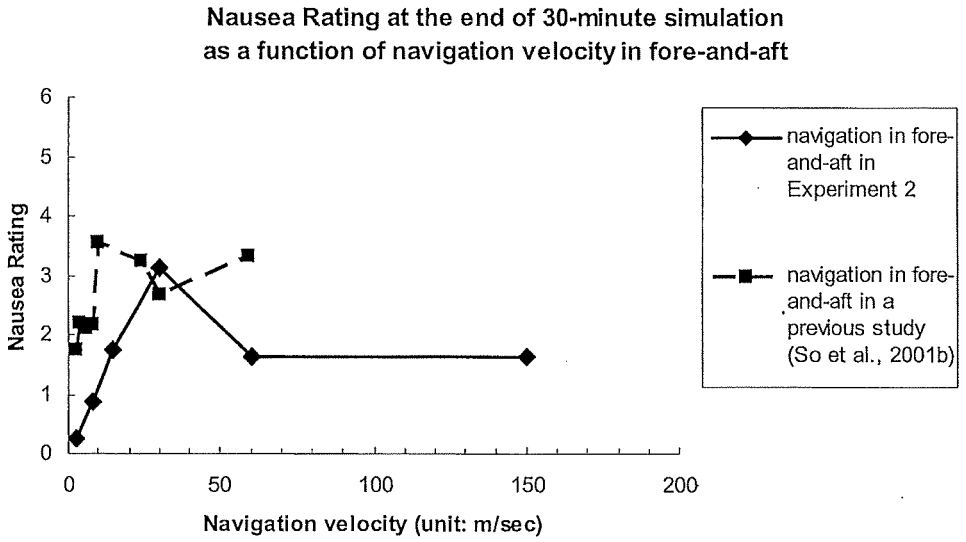

Figure 4.9 Nausea ratings as a function of navigation velocities in fore-and-aft (results from a previous experiment and this experiment). Each square-shaped data point represents average data of 12 participants. Each diamond-shaped data point represents average data of 8 participants.

Table 4.11 R.M.S velocity, SF, Spatial Velocity and nausea ratings reported by subjects at the end of 30-min VR simulation of experiment conducted by So et al., 2001b and Experiment 2

No.	VE	R.M.S Velocity (m/sec)	Average SF (cycle/deg)	SV (m/sec* cycle/de	Nausea rating at the end of 30-min simulation
1	A previous study (So et al., 2001b)	3	0.26	0.78	1.75
2	A previous study (So et al., 2001b)	4	0.26	1.04	2.20
3	A previous study (So et al., 2001b)	6	0.26	1.56	2.10
4	A previous study (So et al., 2001b)	8	0.26	2.08	2.17
5	A previous study (So et al., 2001b)	10	0.26	2.60	3.55
6	A previous study (So et al., 2001b)	24	0.26	6.26	3.25
7	A previous study (So et al., 2001b)	30	0.26	7.80	2.67
8	A previous study (So et al., 2001b)	60	0.26	15.60	3.33
9	Experiment 2	3	0.10	0.30	0.25
10	Experiment 2	8	0.10	0.80	0.88
11	Experiment 2	15	0.10	1.50	1.75
12	Experiment 2	30	0.10	3.00	3.13
13	Experiment 2	60	0.10	6.00	1.63
14	Experiment 2	150	0.10	15.00	1.63

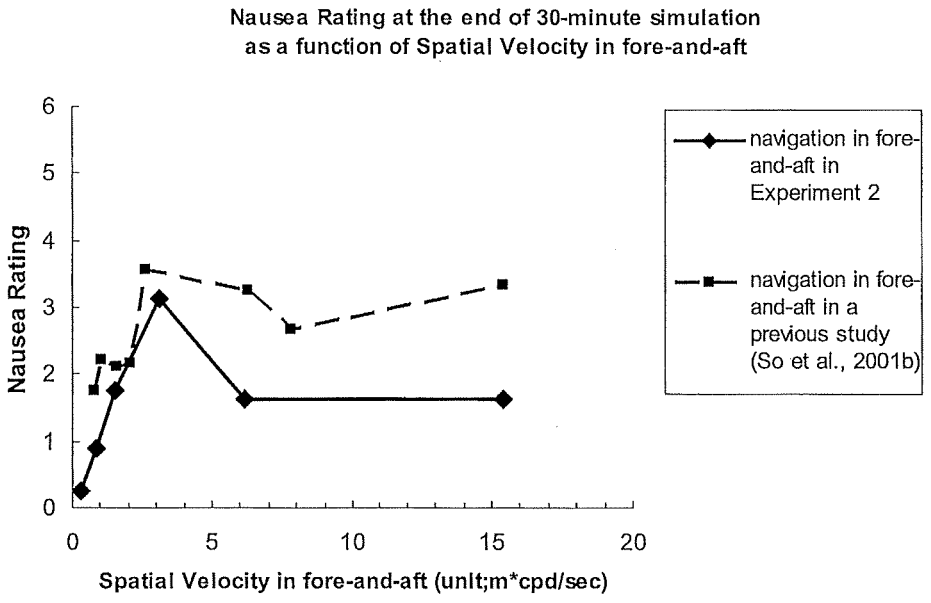

Figure 4.10 Nausea ratings as a function of Spatial Velocity in fore-and-aft (results from a previous experiment and this experiment). Each square-shaped data point represents

average data of 12 participants. Each diamond-shaped data point represents average data of 8 participants.

Table 4.12 R.M.S velocity, SF, Spatial Velocity and increased SSQ total scores reported by subjects at the end of 30-min VR simulation of experiment conducted by So et al., 2001b and Experiment 2

No.	VE	R.M.S Velocity (m/sec)	Average SF (cycle/deg)	SV (m/sec*cycle/deg)	Increased SSQ total
1	A previous study (So et al., 2001b)	3	0.26	0.78	29.50
2	A previous study (So et al., 2001b)	4	0.26	1.04	33.90
3	A previous study (So et al., 2001b)	6	0.26	1.56	27.00
4	A previous study (So et al., 2001b)	8	0.26	2.08	47.10
5	A previous study (So et al., 2001b)	10	0.26	2.60	46.00
6	A previous study (So et al., 2001b)	24	0.26	6.26	46.10
7	A previous study (So et al., 2001b)	30	0.26	7.80	35.00
8	A previous study (So et al., 2001b)	60	0.26	15.60	60.00
9	Experiment 2	3	0.10	0.30	15.43
10	Experiment 2	8	0.10	0.80	29.45
11	Experiment 2	15	0.10	1.50	36.47
12	Experiment 2	30	0.10	3.00	38.80
13	Experiment 2	60	0.10	6.00	48.62
14	Experiment 2	150	0.10	15.00	42.08

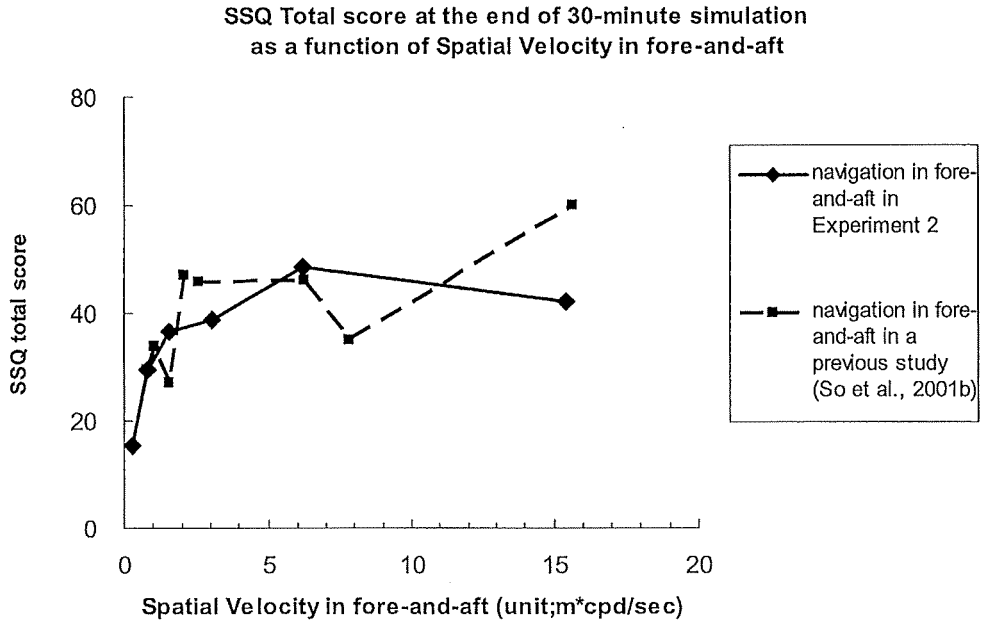

Figure 4.11 SSQ total scores as a function of Spatial Velocity in fore-and-aft (results from a previous experiment and this experiment). Each square-shaped data point epresents average data of 12 participants. Each diamond-shaped data point represents average data of 8 participants.

Chapter 5 Effects of navigation velocities in lateral on level of cybersickness (Experiment 3)

5.1 Objectives

The purpose of this experiment is to study the effects of different levels of navigation velocities in lateral on the level of cybersickness in the Virtual Environment. We aim to determine the relationships among navigation velocities in lateral, rated levels of vection, and rated levels of cybersickness. We proposed a nonlinear relationship between navigation velocity and levels of cybersickness. We hypothesized that increasing navigation velocity in lateral would increase severity of sickness up to a certain level, beyond which, the sickness would decline. Moreover, the results of this experiment will be compared with the results from Experiment 2 to further exam the external validity of the findings from Experiment 1,

5.2 Methodology

5.2.1 Participants

Sixteen male Chinese and sixteen female Chinese volunteers between 19 and 28 years of age participated in Experiment 3. Each of them was paid HK$50 as compensation for his/her time. All participants were consented volunteers who were

healthy and free of medication and illness. The Human Subject and Research Ethics Committee at the Hong Kong University of Science and Technology approved the experiments.

5.2.2 Apparatus and Virtual Reality Simulations

The virtual scene was constructed using a Virtual Reality authoring software (World Tool Kit, Release 9) running on a Silicon Graphics Onyx II (Silicon Graphics, Inc.) workstation. The program was written in C++ language. The VE was presented on a V8 (Virtual Research Systems, Inc.) LCD HMD with a field-of-view of 48 degree in horizontal and 36 degree in vertical. The images were presented on the head mounted display in binocular mode. A Polhemus 3-Space magnetic tracker (Polhemus, Inc.) was used to measure the head position and orientation at a rate of 30/sec during the VR simulation. The apparatus used in this experiment were exactly the same with those used in Experiment 2 (See Figure 4.1).

The Virtual Environment consisted of a large room with 40m in length, 40m in width and 40m in height (as described in chapter 3, sample snapshots were given in Figure 5.1). All participants were exposed to the same VE, but each group of 8 participants were virtually navigated inside the room in lateral at one of four different r.m.s navigation velocities: 3m/sec, 8m/sec, 15m/sec, 30m/sec. The navigation path was

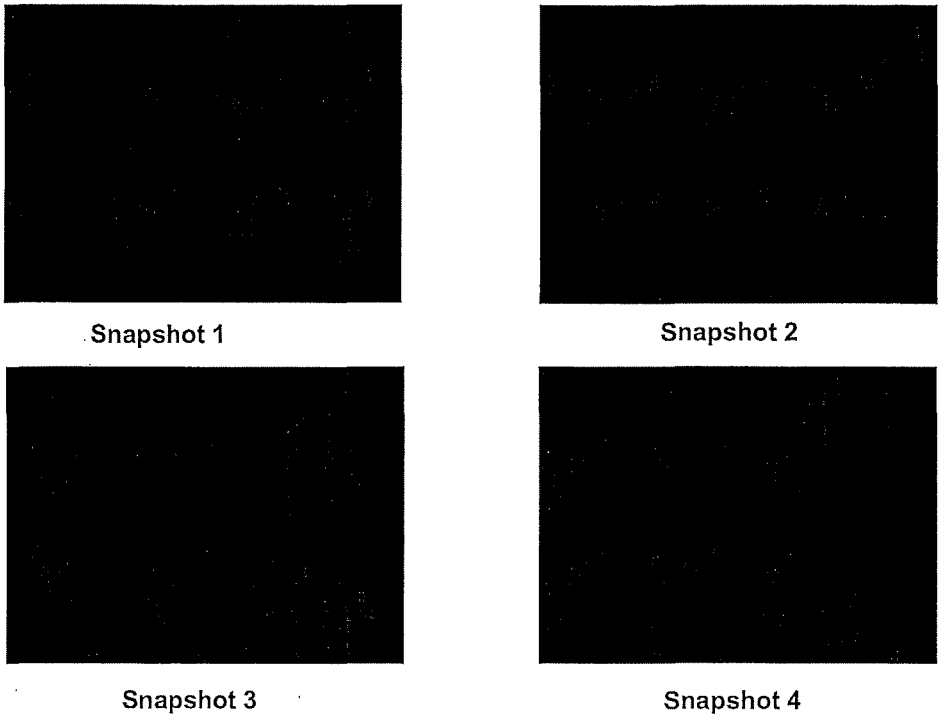

Figure 5.1 Four sample snapshots of the VE used in Experiment 3

presented in sinusoidal wave movements, in which the amplitude was 18m. The calculation of the standard sinusoidal wave:

$$Displacement = ASin2\pi ft$$

with four frequencies used in the experiment,

$$f_1 = 0.0375hz$$

$$f_2 = 0.1hz$$

$$f_3 = 0.1875hz$$

$$f_4 = 0.375hz$$

$$r.m.s.velocity = \sqrt{2}\pi ftA \quad where, A = 18m$$

i.e.,

$$r.m.s.V_1 = \sqrt{2} * \pi * 0.0375 * 18 = 3m/\sec$$

$$r.m.s.V_2 = \sqrt{2} * \pi * 0.1 * 18 = 8m/\sec$$

$$r.m.s.V_3 = \sqrt{2} * \pi * 0.1875 * 18 = 15m/\sec$$

$$r.m.s.V_4 = \sqrt{2} * \pi * 0.375 * 18 = 30m/\sec$$

The average frame rates were 30 frame/second in all the four simulation conditions. It should be noted, due to the time limit, only four velocities were investigated with the range from 3m/sec to 30m/sec.

5.2.3 Experimental design

Root mean square (r.m.s) of navigation velocities of 3m/sec, 8m/sec, 15m/sec, 30m/sec in the lateral axis were investigated. Gender difference was also considered. Experiment 3 was a full factorial between-subject design experiment. Totally 32 (16 male and 16 female) participants took part in the experiment, and each participant was randomly assigned to one navigation condition. Each condition was tested on 8 subjects (4 male and 4 female). The duration of exposure to the VE took 30 minutes.

5.2.4 Procedures and measurements

Once participants came in, participants were asked to read and sign a consent form. And then participants were required to complete a Motion Sickness Susceptibility Survey (MSSS, Appendix F). The subjects' susceptibilities to motion sickness were

recorded. They were used to balance subjects' susceptibilities among different navigation conditions to avoid that, in one particular condition, subjects were biased to have more or less susceptibilities on motion sickness than those in other conditions. Then the participants were then randomly assigned to one of the experimental condition. A short training session was given to each participant. During the training session, participants were educated to distinguish vection from perceived speed of the surround scene and they were reminded to rate only the level of vection. Besides that, they were also educated with the terminologies involved in SSQ, particular, the differences among nausea, dizziness, eyestrain and vertigo.

Then, participants were then asked to complete a pre-exposure SSQ. All participants with a pre-exposure SSQ of more than 2 slight symptoms or a pre-exposure SSQ total score of more than 10 were asked to take a rest for 5-10 minutes with their eyes closed. After that, the participants were asked to fill in another pre-SSQ. If the pre-exposure SSQ total score was less than 10, then the experiment proceeded. However, if the pre-exposure SSQ total score was still more than 10, then the participants were asked to come back for another date. Then 30 minutes Virtual Reality simulation was given. During the 30 minutes exposure, participants were asked to keep sitting in an up-right posture. At five-minute intervals, participants were asked to rate verbally their symptoms of nausea on a seven-point scale (Appendix A) and at ten-minute intervals, they were asked to rate their sensation of vection on a 4-point scale (Appendix C). Vection duration was also recorded by

pressing a button when the participant experienced vection sensation. Participants head tracking history were also recorded during 30 minutes exposure. In order to encourage participants to be more involved in the VE, from time to time, there were some additional pop-up objects, e.g. cross, circle and cubes with letters, suddenly appeared in front of the subject in the environment. Subjects were asked to speak out and describe what they had seen to the experimenter.

After the exposure of VR simulation, participants were asked to complete a post-exposure SSQ. During the simulation, if a participant reported the nausea rating of 6 (that is *moderate nausea, want to stop*), then the VR simulation was terminated and the participant was asked to complete the post-exposure SSQ. A score of 6 was assigned for the remaining verbal rating reports.

5.3 Results

Since data on nausea ratings, vection ratings, vection duration and SSQ measurements obtained in Experiment 3 were normally distributed (results on normal tests were in Appendix D), parametric statistical analysis was applied for analyzing the data. SAS 8.01 and SPSS 11.0 were adopted to analyze the data collected in Experiment 3.

5.3.1 Results on nausea ratings

The mean of nausea ratings reported from participants exposed to VR simulation with different navigation velocities in lateral were shown in Figure 5.2. Data are plotted in function of exposure duration. This figure displayed the over all nausea ratings changing over exposure time as well as different navigation velocities in lateral. Furthermore, it indicated nausea ratings increased with exposure time. Inspection on this figure showed that when navigating at 15m/sec, subjects reported higher nausea rating at each time interval.

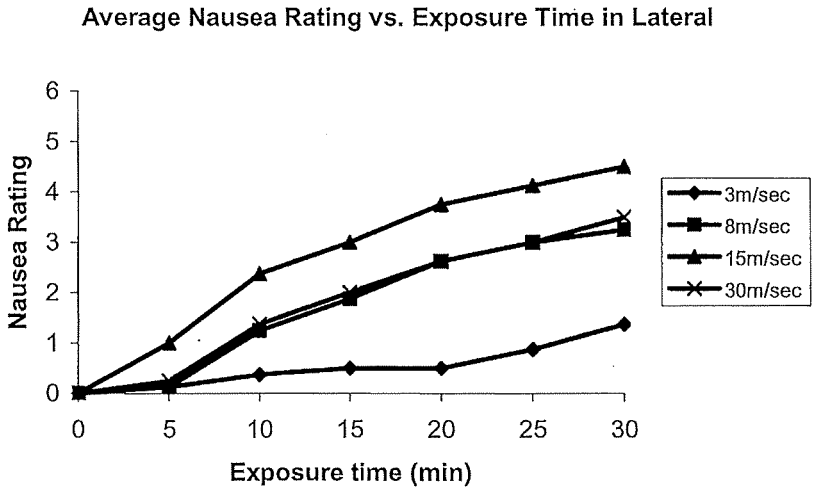

Figure 5.2 The mean of nausea ratings reported from participants exposed to VR simulation with different navigation velocities in lateral. Data are plotted in function of exposure duration. Each data point represents average data of 8 participants.

One ANOVA on nausea ratings was performed to study the effect of navigation velocity in lateral, duration and gender. Navigation velocity and duration of exposure, were found to have significant effects on nausea ratings ($p<0.05$). Gender didn't

show significant difference in producing cybersickness. Moreover, the interaction between navigation condition and gender showed significant effects on nausea ratings ($p<0.05$).

Table 5.1 ANOVA table on nausea ratings analyzing the effects of navigation velocities in lateral, gender and exposure duration for a 30 min VR simulation in Experiment 3.

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Navigation velocity	3	132.73	44.24	17.44	<0.01
Gender	1	0.36	0.36	0.14	0.71
Duration	6	266.09	44.35	17.48	<0.01
Condition*Gender	3	22.74	7.59	2.99	0.03
Condition*Duration	18	45.80	2.54	1.00	0.46
Gender*Duration	6	1.36	0.23	0.09	1.00
Condition*Gender*Duration	18	14.39	0.80	0.32	1.00
Error	168	426.25	2.54		
Total	223	909.75			

For further investigate the effects of navigation velocities in laterals multiple comparison analysis using Student-Newman-Kuels tests of the ANOVA results in Table 5.1 were shown in Table 5.2. It confirmed that nausea ratings were significantly different among four navigation conditions in lateral ($p<0.01$), nausea ratings increased with increasing navigation velocities and peaked at 15m/sec, and then dropped at 30m/sec. On the other hand, after exposure to VR simulations for 5

minutes, nausea rating increased significantly up to 20 minutes, and then nausea ratings stabilized for the rest 10 minutes.

Table 5.2 Student-Newman-Kuels (SNK) tests indicating the effects of (a) navigation velocity, (b) duration, and (c) gender on nausea ratings for a 30 min VR simulation in Experiment 3

(a) SNK groupings on the effects of navigation velocity

SNK	Nausea	Number	Velocity
A	2.7	56	15m/sec
B	1.8	56	30m/sec
B	1.7	56	8m/sec
C	0.5	56	3m/sec

(b) SNK groupings on the effects of duration

SNK Grouping		Nausea Rating	Number	Duration (min)
	A	3.1	32	30
B	A	2.8	32	25
B	A	2.4	32	20
B	C	1.8	32	15
	C	1.4	32	10
	D	0.4	32	5
	D	0.0	32	0

Since ANOVA table 5.1 indicated that the interaction effect between gender and navigation velocity in lateral was also significant, Figure 5.3 described the interaction plot of gender and navigation velocity on nausea rating in Experiment 3. From this figure, obviously, the significant interaction effect was possibly because

male subjects reported higher nausea rating at 3m/sec than female subjects (with mean of 0.89 reported from male subject and 0.14 reported from female subject) while males reported lower nausea ratings at 8m/sec than female subjects (with mean of 1.32 reported from male subject and 2.21 reported from female subject). However, both two curves depicted similar pattern, i.e., a nonlinear relationship between navigation velocities and level of nausea rating. Nausea ratings increased with increasing navigation velocities in lateral from 3m/sec to 15m/sec and decreased at 30m/sec reported both from male subjects and female subjects. It was reasonable to believe that the main effects of navigation velocity on level of nausea rating was robust both applied for male and female subjects.

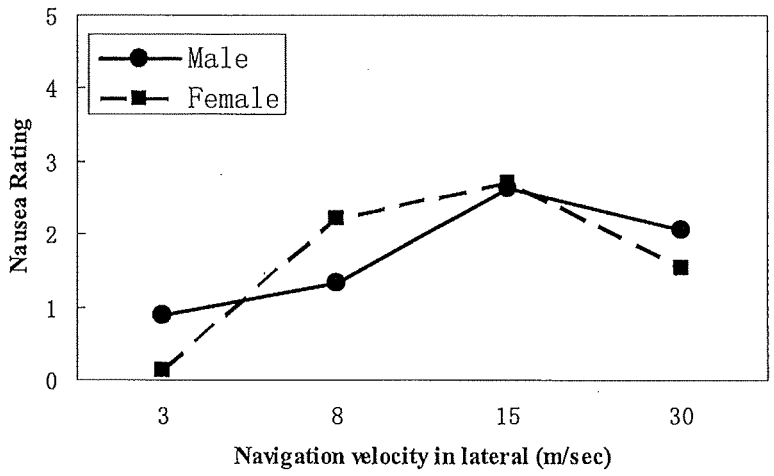

Figure 5.3 Interaction plot of gender and navigation velocity on nausea rating in Experiment 3.

Figure 5.4 illustrated the mean of nausea ratings with standard deviation reported from participants at the end of 30-min VR simulation with different navigation velocities in lateral. Obviously, the figure showed a nonlinear relationship between nausea rating and navigation velocities.

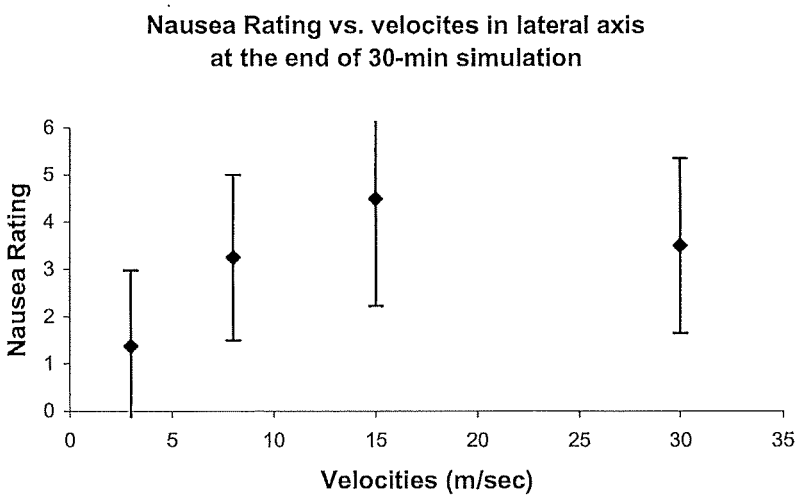

Figure 5.4 The mean of nausea ratings with standard deviation reported from participants at the end of 30-min VR simulation with different navigation velocities in lateral. Data are plotted in function of velocities. Each data point represents average data of 8 participants.

5.3.2 Vection rating and vection duration

The mean of vection ratings reported from participants exposed to VR simulation with different navigation velocities in lateral were shown in Figure 5.5. Inspection on

this figure showed that vection rating increased for the first 10 minutes, after that, the vection ratings became statistically the same. Table 5.3 showed the ANOVA test results of the effects of gender, exposure duration and navigation velocities on vection ratings. Exposure duration, gender and navigation velocity were found significantly affecting the vection ratings ($p<0.05$). However, Student-Newman-Keuls test results shown in Table 5.4 indicated that vection ratings were not significantly different among 10, 20 or 30 minutes exposure. In the meanwhile, Table 5.4 also indicated that vection ratings were significantly higher when navigation velocity was 15m/sec than other levels. This result was consistent with the fact that subjects reported significantly highest level of nausea ratings at 15m/sec compared with other navigation velocities. SNK results also showed that female subjects reported significantly higher vection ratings than male subjects. The possible reason may be because female's sensitivity could be higher than male in terms of lateral navigation in VEs. However, this is only a implication from this study, it need further proof in the future.

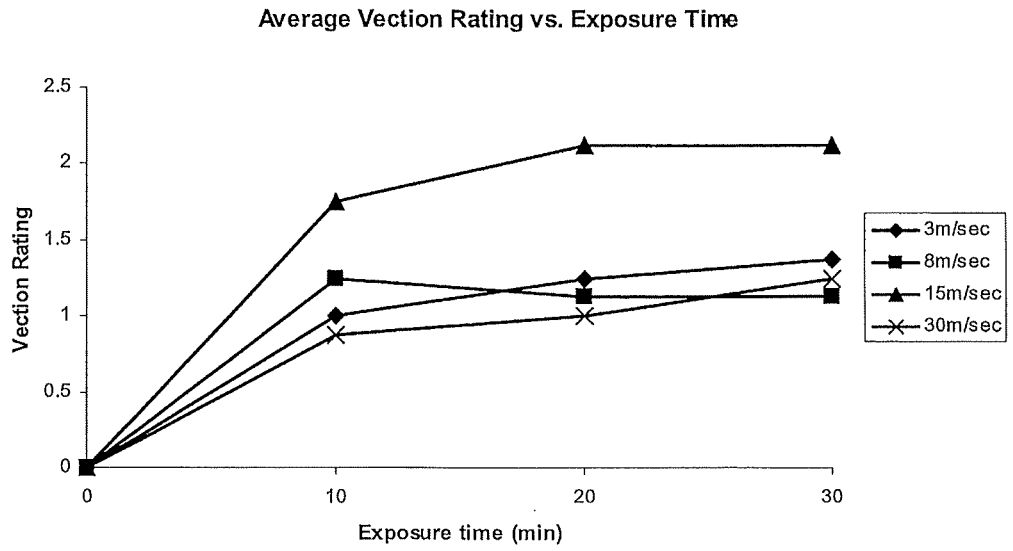

Figure 5.5 The mean of vection ratings reported from participants exposed to VR simulation with different navigation velocities in lateral. Data are plotted in function of exposure duration. Each data point represents average data of 8 participants.

Table 5.3 ANOVA table on vection ratings analyzing the effects of gender, exposure duration, and navigation velocity for a 30 min VR simulation in Experiment 3.

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	10.28	3.43	4.67	<0.01
Gender	1	3.13	3.13	4.26	<0.01
Duration	3	45.03	15.01	20.44	<0.01
Velocity*Gender	3	8.06	2.69	3.66	0.02
Velocity*Duration	9	4.41	0.49	0.67	0.74
Gender*Duration	3	1.06	0.35	0.48	0.70
Velocity*Gender*Duration	9	3.50	0.39	0.53	0.85
Error	96	70.50	0.73		
Total	127	145.97			

Table 5.4 Student-Newman-Kuels (SNK) tests indicating the effects of (a) navigation velocity, (b) duration, and (c) gender on vection ratings for a 30 min VR simulation in Experiment 3

(a) SNK groupings on the effects of navigation velocity

SNK	Vection Rating	Number	Velocity
A	1.5	32	15m/sec
B	0.91	32	3m/sec
B	0.88	32	8m/sec
B	0.78	32	30m/sec

(b) SNK groupings on the effects of duration

SNK Grouping	Vection Rating	Number	Duration (min)
A	1.47	32	30
A	1.38	32	20
A	1.22	32	10
B	0.00	32	0

(c) SNK groupings on the effects of gender

SNK Grouping	Vection Rating	Number	Gender
A	1.17	64	female
B	0.86	64	male

ANOVA table 5.3 indicated that the interaction effect between gender and navigation velocity in lateral was also significant. Figure 5.6 described the interaction plot of

gender and navigation velocity on vection rating in Experiment 3. From this figure, obviously, female subjects seemed reported statistically same levels of vection ratings among four levels navigation velocities in lateral; while male subjects reported a nonlinear relationship between navigation velocities in lateral and vection ratings. It was possible that the sensitivities to navigation velocities in lateral may be different to male subjects and female subjects. However, it need further study in the future to draw such conclusion.

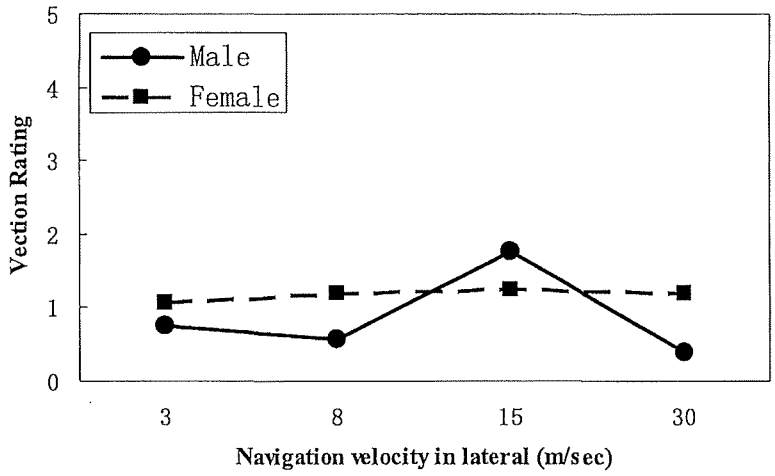

Figure 5.6 Interaction plot of gender and navigation velocity on vection rating in Experiment 3.

Figure 5.7 showed the vection duration as a function of 4 levels of navigation velocities. It showed a flat change in vection duration as varied by different navigation velocities. Similarly as vection ratings, subjects reported highest vection duration with navigation velocity at 15m/sec, although the effect was not significant.

Table 5.5 showed the ANOVA test results of the effects of gender, and navigation velocities on vection duration, indicating no significant difference among four levels of vection duration.

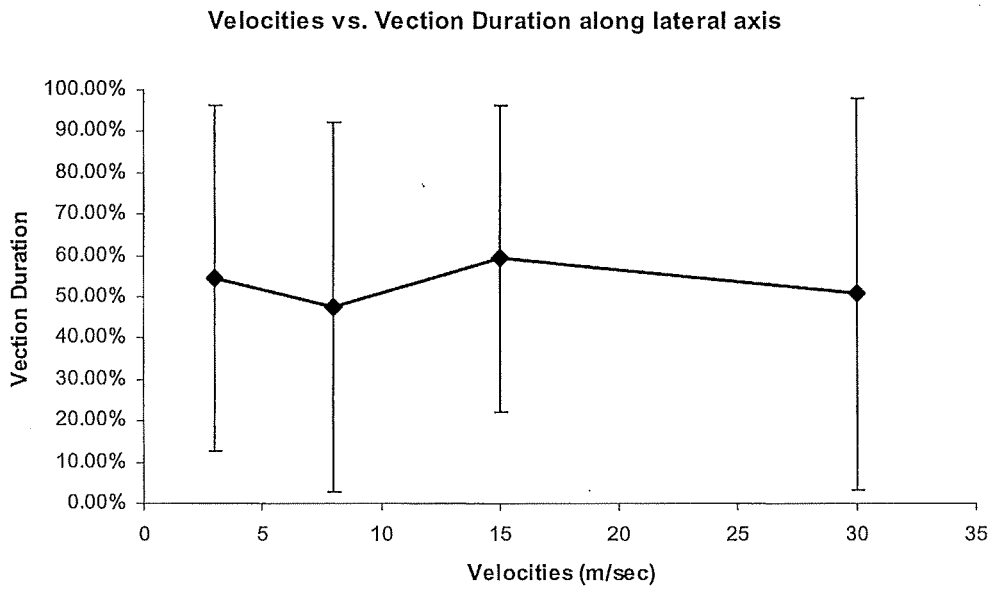

Figure 5.7 The mean of vection duration with standard deviation reported from participants during 30-min VR simulation with different navigation velocities in fore-and-aft. Data are plotted in function of velocities. Each data point represents average data of 8 participants

Table 5.5 ANOVA table on vection duration analyzing the effects of gender, and navigation velocities for a 30 min VR simulation in Experiment 3

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	0.06	0.02	0.11	0.95
Gender	1	0.09	0.09	0.47	0.50
Velocity*Gender	3	0.42	0.14	0.77	0.52
Error	24	4.34	0.18		
Total	31	4.90			

In this experiment, we found that higher level of vection rating possibly implied higher level of nausea rating. In Experiment 2, percentage of vection duration also correlated with nausea ratings. However, in this experiment, navigation velocities didn't significantly affect the percentage of vection duration. This may imply that measurement of vection rating and vection duration are both useful in order to fully characterize the nature of vection in VR simulation. Different patterns on vection rating and vection duration were found which was consistent with a literature by Flanagan et al., 2002.

5.3.3 Simulator Sickness Questionnaire scores

Figure 5.8 showed the mean of increased SSQ scores reported from participants after exposure of 30-min VR simulation with different navigation velocities in lateral. Data are plotted in function of velocity. Each data point represents average data of 8 participants. From this figure, we can see a trend that SSQ scores increased with increasing navigation velocities up to around 15m/sec, after that the sickness level stabilized. Table 5.7 showed the ANOVA results of the effects of gender and

navigation velocities on the four SSQ scores. Gender didn't show significant effect on all the SSQ scores ($p>0.05$). Navigation velocity had significant effects on SSQ nausea score ($p<0.05$) and total score. Further SNK results showed that subjects reported significantly higher SSQ nausea scores with navigation velocity at 15m/sec than navigation velocity at 3m/sec. Similar patterns were found on nausea rating.

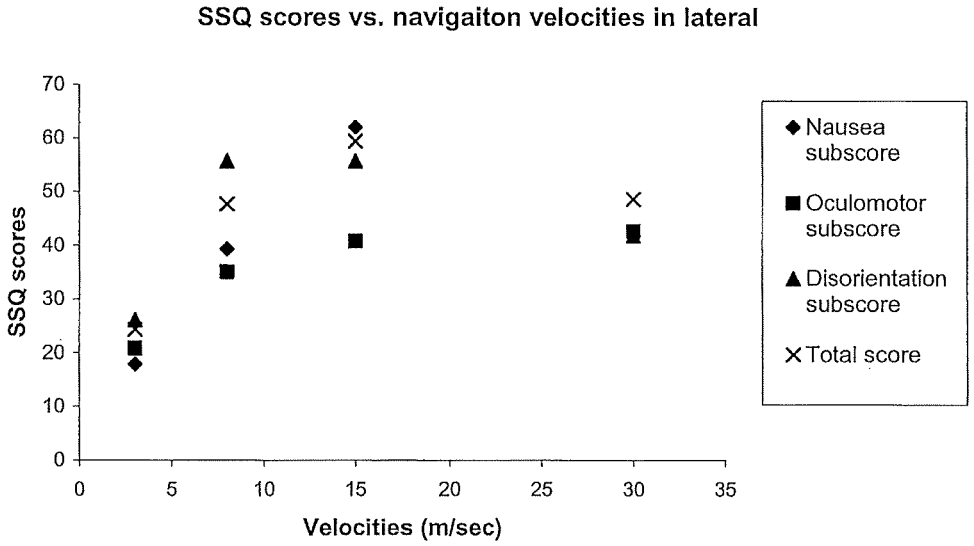

Figure 5.8 The mean of increased SSQ scores reported from participants after exposure of 30-min VR simulation with different navigation velocities in lateral. Data are plotted in function of velocity. Each data point represents average data of 8 participants.

Table 5.6 ANOVA table on SSQ scores analyzing the effects of gender, and navigation velocities for a 30 min VR simulation in Experiment 3

a) Dependent variable: Nausea subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	8247.93	2749.31	3.8	0.02
Gender	1	11.38	11.38	0.02	0.90
Velocity*Gender	3	2696.22	898.74	1.24	0.32
Error	24	17337.71	722.40		
Total	31	28293.23			

b) Dependent variable: Oculomotor subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	2332.37	777.46	2.75	0.07
Gender	1	44.89	44.89	0.16	0.69
Velocity*Gender	3	1441.80	480.60	1.70	0.19
Error	24	6794.22	283.09		
Total	31	10613.27			

c) Dependent variable: Disorientation subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	4765.44	1588.48	1.72	0.19
Gender	1	151.38	151.38	0.16	0.69
Velocity*Gender	3	7332.85	2444.28	0.80	0.07
Error	24	22137.81	922.41		
Total	31	34387.48			

d) Dependent variable: Total score

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	5759.39	1919.80	4.13	0.02
Gender	1	1.75	1.75	0.00	0.95
Velocity*Gender	3	3561.59	1187.20	2.55	0.08
Error	24	11155.11	464.80		
Total	31	20477.85			

Table 5.7 Student-Newman-Kuels (SNK) tests indicating the effects of navigation velocity on a) nausea score, b) total score of a 30 min VR simulation in Experiment 3

a) effects on nausea score

SNK Grouping		Nausea Subscore	Number	Velocity
	A	62.01	8	15m/sec
B	A	41.74	8	30m/sec
B	A	39.35	8	8m/sec
B		16.70	8	3m/sec

b) effects on total score

SNK Grouping		Total Score	Number	Velocity
	A	57.50	8	15m/sec
B	A	45.82	8	30m/sec
B	A	44.41	8	8m/sec
B		20.57	8	3m/sec

Figure 5.9 and Figure 5.10 showed the mean of increased SSQ nausea subscore / total score with standard deviation reported from participants after exposure of 30-min VR simulation with different navigation velocities in lateral.

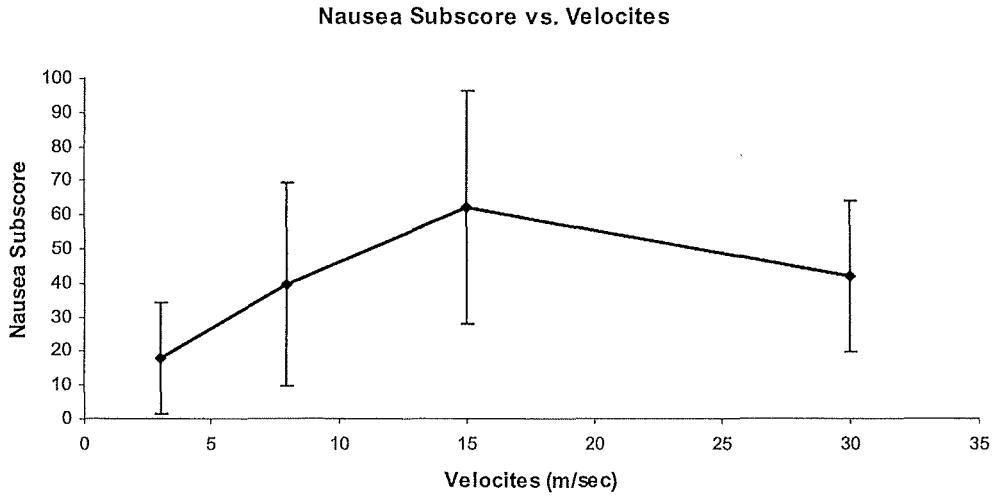

Figure 5.9 The mean of increased SSQ nausea subscore with standard deviation reported from participants after exposure of 30-min VR simulation with different navigation velocities in lateral. Data are plotted in function of velocity. Each data point represents average data of 8 participants.

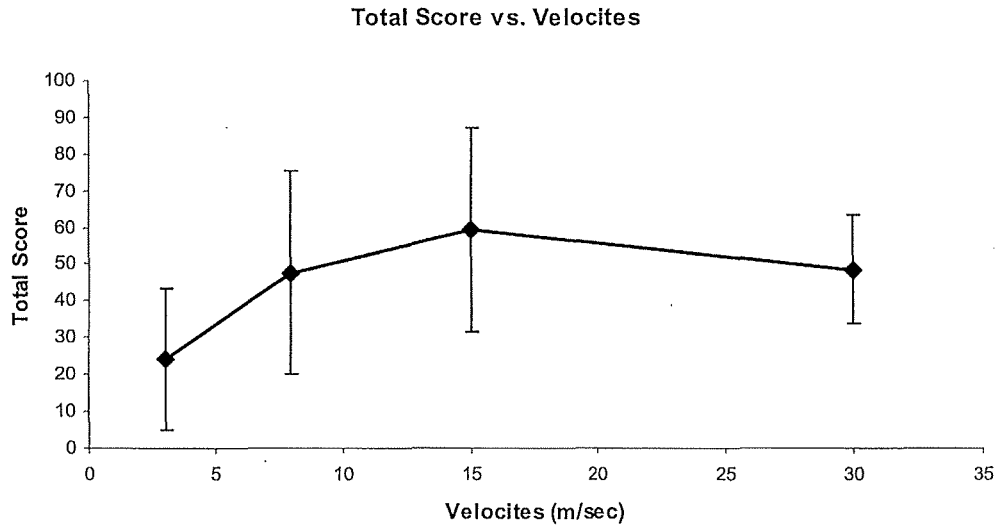

Figure 5.10 The mean of increased SSQ total score with standard deviation reported from participants after exposure of 30-min VR simulation with different navigation

velocities in lateral. Data are plotted in function of velocity. Each data point represents average data of 8 participants.

5. 4 Discussion

5.4.1 Effects of exposure duration

Navigating in lateral in VEs could significantly produce cybersickness ($p<0.01$). Nausea ratings increased significantly with increasing exposure duration up to around 20 minutes. While vection ratings increased for the first 10 minutes, after that, the vection rating became statistically the same with increasing exposure duration.

5.4.2 Effects of gender

Results from this experiment indicated that gender is not significantly affecting the levels of cybersickness indicated by nausea ratings or SSQ scores. These results were similar as those found from Experiment 2. However, female reported significantly higher level of vection rating than male in this experiment. It needs to be further confirmed that whether females are more sensitive to lateral navigation inside VEs than males.

5.4.3 Effects of navigation velocity

Results obtained from this experiment indicated that nausea ratings increased with significantly increasing navigation velocity in lateral axis up to 15m/sec, and then nausea ratings significantly decreased at 30m/sec. Subjects reported highest nausea ratings when navigating at 15m/sec, while reported lowest nausea ratings when navigating at 3m/sec. Similar patterns were found on SSQ scores, i.e., subjects reported significantly higher SSQ nausea subscore and total score at 15m/sec. However, SSQ scores didn't significantly decreased after 15m/sec. It is reasonable since the measurement of SSQ score is more complicated than nausea rating. SSQ scores contain more dimensions.

Results on vection ratings also indicated that subjects experienced higher strength of vection when navigating at 15m/sec. It was confirmed and consistent with previous founding that vection was associated with sickness symptoms and higher level of vection possibly caused higher level of sickness in VR simulation.

However, in this experiment, the percentage of vection duration was not significantly affected by navigation velocity. Among four VR simulation conditions, the average of vection duration reported from participants were all around 50%. While in Experiment 2, subjects reported low average vection duration at low navigation velocity (6.88% at 3m/sec in fore-and-aft; 20.38% at 8m/sec in fore-and-aft). It seemed when navigating in lateral, participants experienced more or simliar self

motion than navigating in fore-and-aft. Further researches may be needed to study this difference. Moreover, nausea rating peaked at 15m/sec in lateral while peaked at 30m/sec in fore-and-aft. Although the nonlinear patterns were similar between the different navigation velocities either in fore-and-aft or in lateral and level of cybersickness, the nonlinear curves may possibly be different somewhat.

5.4.4 Correlations between dependent variables

Correlations between nausea ratings, vection ratings, vection duration and SSQ scores obtained at the end of 30 min VR simulation in Experiment 3 were shown in Table 5.8. From this table, patterns of vection duration and vection rating seemed different. Correlations between vection duration and nausea ratings, SSQ scores were not significantly; correlation between vection rating and nausea rating was significant; correlation between vection duration and vection rating was significantly. On the other hand, nausea rating and SSQ scores were highly correlated ($p<0.05$). These findings were quite similar as we found in Experiment 2.

Table 5.8 Correlations between nausea ratings, vection ratings, vection durations and SSQ scores at the end of 30 min VR simulation in Experiment 3

		Nausea Rating	Vection Rating	Vection Duration	SSQ_NS	SSQ_OS	SSQ_DS	SSQ_TS
Nausea Rating	Pearson Correlation	1.00	0.42**	0.13	0.87**	0.42*	0.51**	0.73**
	Sig.)		0.02	0.47	<0.01	<0.02	<0.01	<0.01
Vection Rating	Pearson Correlation		1.00	0.61**	0.32	0.08	0.14	0.23
	Sig.			<0.01	0.07	0.65	0.44	0.21
Vection Duration	Pearson Correlation			1.00	-0.03	-0.11	0.01	-0.05
	Sig.				0.88	0.56	0.98	0.79
SSQ_NS	Pearson Correlation				1.00	0.47**	0.58**	0.83**
	Sig.					<0.01	<0.01	<0.01
SSQ_OS	Pearson Correlation					1.00	0.78**	0.85**
	Sig.						<0.01	<0.01
SSQ_DS	Pearson Correlation						1.00	0.90**
	Sig.							<0.01
SSQ_TS	Pearson Correlation							1.00
	Sig.							

** Corrleation is significant at the 0.01 level.

5.4.5 Comparing results of Experiment 2 and Experiment 3

As found in Experiment 1a, it is concluded with navigation in VEs, scene movements in lateral or vertical may possibly produce more sickness among users than scene movements in fore-and-aft. Comparing results of Experiment 2 and Experiment 3 hence provides a chance for us to verify this conclusion. Table 5.9 listed the R.M.S velocities, average SF, SV, average nausea ratings and SSQ total scores collected in Experiment 2 and Experiment 3. Figure 5.11 and Figure 5.12 compared the nausea

ratings and SSQ total scores with navigation in fore-and-aft and lateral. From these two figures, it was obviously that, with the same level of Spatial Velocity, subjects reported higher nausea rating and SSQ total score when navigating in lateral than navigating in fore-and-aft.

Table 5.9 R.M.S velocity, SF, Spatial Velocity, nausea ratings at the end of 30-min VR simulation and increased SSQ total scores reported by subjects of Experiment 2 and Experiment 3

No.	VE	R.M.S Velocity (m/sec)	Average SF (cpd)	SV (m/sec*cpd)	Nausea rating at 30-min	SSQ total score
1	Experiment 3	3	0.097	0.291	1.38	24.31
2	Experiment 3	8	0.097	0.776	3.25	47.69
3	Experiment 3	15	0.097	1.455	4.5	59.37
4	Experiment 3	30	0.097	2.91	3.5	48.62
5	Experiment 2	3	0.103	0.309	0.25	15.43
6	Experiment 2	8	0.103	0.824	0.88	29.45
7	Experiment 2	15	0.103	1.545	1.75	36.47
8	Experiment 2	30	0.103	3.09	3.13	38.80
9	Experiment 2	60	0.103	6.18	1.63	48.62
10	Experiment 2	150	0.103	15.45	1.63	42.08

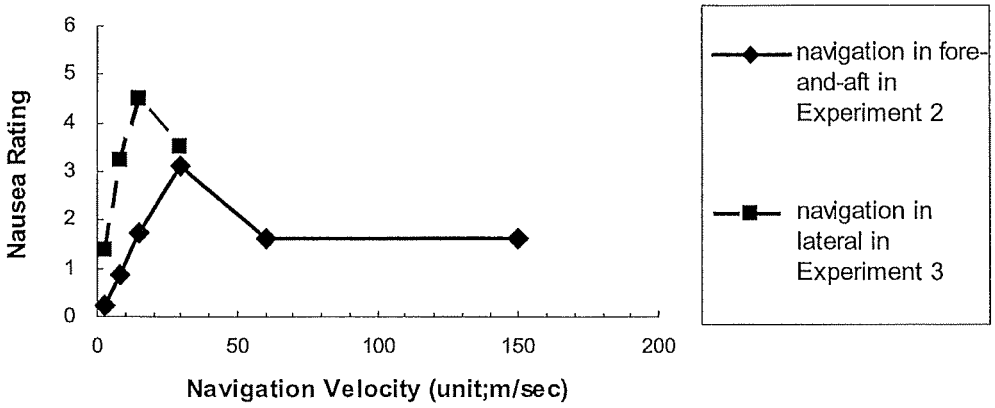

Figure 5.11 Nausea ratings as a function of navigation velocities (results from Experiment 2, i.e, SV in fore-and-aft; and from Experiment 3, i.e., SV in lateral). Each square-shaped data point represents average data of 8 participants. Each diamond-shaped data point represents average data of 8 participants.

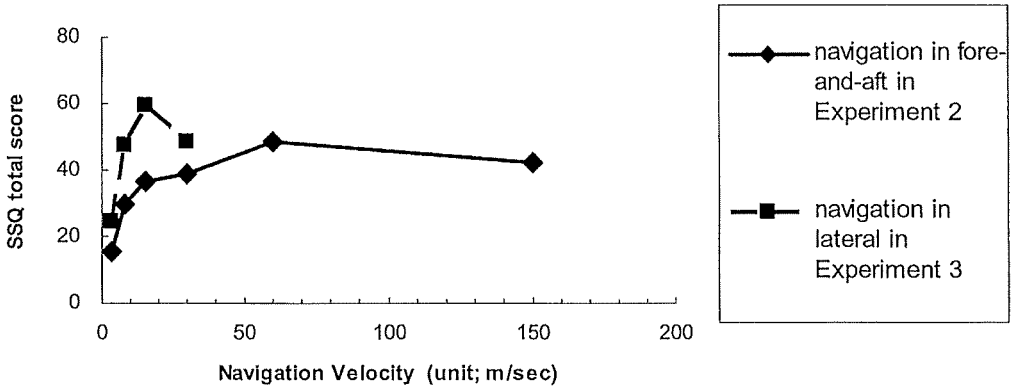

Figure 5.12 SSQ total scores as a function of navigation velocities (results from Experiment 2, i.e, SV in fore-and-aft; and from Experiment 3, i.e., SV in lateral). Each square-shaped data point represents average data of 8 participants. Each diamond-shaped data point represents average data of 8 participants.

Chapter 6 Effects of navigation velocities in yaw on level of cybersickness (Experiment 4)

6.1 Objectives

The purpose of this experiment is to determine the effects of different levels of navigation velocities in yaw in VR simulations on the level of cybersickness. Hu et al. (1989) used a rotating drum to provoke visually induced motion sickness and studied the effects of the speed of the rotating drum on symptoms of motion sickness. Hu demonstrated a curvilinear relationship between speed of drum rotation and severity of symptoms of motion sickness. We hypothesized a nonlinear relationship existed between levels of navigation velocities in yaw and levels of cybersickness. Four level of navigation velocity (r.m.s) were used: 7.6deg/sec, 20.4deg/sec, 38.2deg/sec and 76.4deg/sec.

6.2 Methodology

6.2.1 Participants

Sixteen male Chinese and sixteen female Chinese volunteers between 19 and 28 years of age participated in the experiments. Each of them was paid HK$50 as compensation for his/her time. All participants were consented volunteers who were

healthy and free of medication and illness. The Human Subject and Research Ethics Committee at the Hong Kong University of Science and Technology approved the experiments.

6.2.2 Apparatus and Virtual Reality Simulations

The virtual scene was constructed using a Virtual Reality authoring software (World Tool Kit, Release 9) running on a Silicon Graphics Onyx II (Silicon Graphics, Inc.) workstation. The program was written in C++ language. The VE was presented on a V8 (Virtual Research Systems, Inc.) LCD HMD with a field-of-view of 48 degree in horizontal and 36 degree in vertical. The images were presented on the HMD in binocular mode. A Polhemus 3-Space magnetic tracker (Polhemus, Inc.) was used to measure the head position and orientation at a rate of 30/sec during the VR simulation. Apparatus used in this experiment were illustrated in Figure 4.1. Four snapshots of the VE used in this experiment were illustrated in Figure 6.1.

The Virtual Environment consisted of a large room with 40m in length, 40m in width and 40m in height (as described in Chapter 3). All participants were exposed to the same VE, but each group of 8 participants were virtually navigated inside the room in yaw at one of four different r.m.s navigation velocities: 7.6deg/sec, 20.4deg/sec, 38.2deg/sec and 76.4deg/sec. The navigation path was presented in sinusoidal wave movements, in which the

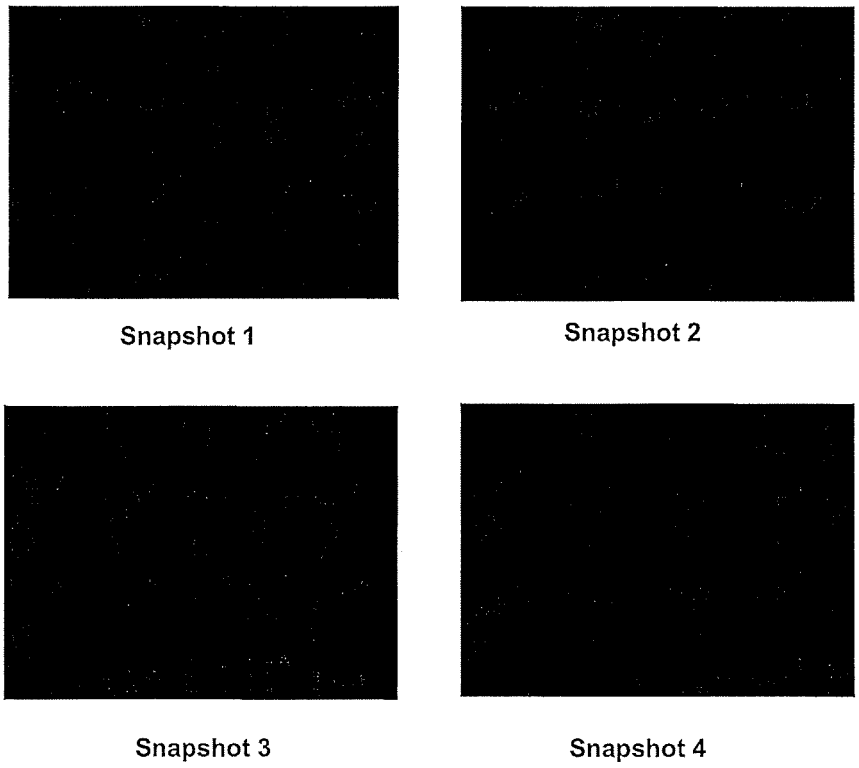

Figure 6.1 Four snapshots of virtual environment used in Experiment 4

amplitude was 90deg, and the visual scene motion frequencies were 0.0375hz, 0.1hz, 0.1875hz and 0.375hz. The scene motion frequencies were corresponding to the frequencies studied in Experiment 3 so that we could make comparisons with the results obtained from Experiment 3 and Experiment 4. It was not strange when participants navigated in VEs with lateral oscillation and yaw oscillation, the scene movements were similar in some extent. The calculation of the standard sinusoidal wave:

$$Displacement = ASin2\pi ft$$

with four frequencies used in the experiment,

$$f_1 = 0.0375\ hz$$
$$f_2 = 0.1\ hz$$
$$f_3 = 0.1875\ hz$$
$$f_4 = 0.375\ hz$$

$$r.m.s\ \ Velocity = \frac{2\pi fA}{\sqrt{2}} = \sqrt{2}\pi fA, where, A = 0.8rad$$

$$r.m.s\ V_1 = \sqrt{2}\pi f_1 A = 0.1333\ radian/\sec = 7.6\deg/\sec$$
$$r.m.s\ V_2 = \sqrt{2}\pi f_2 A = 0.3554\ radian/\sec = 20.4\deg/\sec$$
$$r.m.s\ V_3 = \sqrt{2}\pi f_3 A = 0.6664\ radian/\sec = 38.2\deg/\sec$$
$$r.m.s\ V_4 = \sqrt{2}\pi f_4 A = 1.3329\ radian/\sec = 76.4\deg/\sec$$

The average frame rates were 30 frame/second in all the four simulation conditions.

6.2.3 Experimental design

Navigation velocities of 7.6deg/sec, 20.4deg/sec, 38.2deg/sec and 76.4deg/sec root mean square (r.m.s) in the yaw axis were investigated. Gender difference was also considered. Experiment 4 was a full factorial between-subject design experiment. Totally 32 (16 male and 16 female) participants took part in the experiment, and each participant was randomly assigned to one navigation condition. Each condition was tested on 8 subjects (4 male and 4 female). The duration of exposure to the VE took 30 minutes.

6.2.4 Procedures and measurements

Once participants came in, participants were asked to read and sign a consent form. And then participants were required to complete a Motion Sickness Susceptibility Survey (MSSS). The subjects' susceptibilities to motion sickness were recorded. They were used to balance subjects' susceptibilities among different navigation conditions to avoid that, in one particular condition, subjects were biased to have more or less susceptibilities on motion sickness than those in other conditions. Then the participants were randomly assigned to one of the experimental condition. A short training session was given to each participant. During the training session, participants were educated to distinguish vection from perceived speed of the surround scene and they were reminded to rate only the level of vection. Besides that, they were also educated with the terminologies involved in SSQ, particular, the differences among nausea, dizziness, eyestrain and vertigo.

Then, participants were then asked to complete a pre-exposure SSQ. All participants with a pre-exposure SSQ of more than 2 slight symptoms or a pre-exposure SSQ total score of more than 10 were asked to take a rest for 5-10 minutes with their eyes closed. After that, the participants were asked to fill in another pre-SSQ. If the pre-exposure SSQ total score was less than 10, then the experiment proceeded. However, if the pre-exposure SSQ total score was still more than 10, then the participants were asked to come back at another date. Then 30 minutes Virtual Reality simulation was given. During the 30 minutes exposure, participants were asked to keep sitting in an up-right posture. At five-minute intervals, participants

were asked to rate verbally their symptoms of nausea on a seven-point scale (Appendix A) and at ten-minute intervals, they were asked to rate their sensation of vection on a 4-point scale (Appendix C). Vection duration was also recorded by pressing a button when the participant experienced vection sensation. Participants head tracking history were also recorded during 30 minutes exposure. In order to encourage participants to be more involved in the VE, from time to time, there were some additional pop-up objects, e.g. cross, circle and cubes with letters, suddenly appeared in front of the subject in the environment. Subjects were asked to speak out and describe what they had seen to the experimenter.

After the exposure of VR simulation, participants were asked to complete a post-exposure SSQ. During the simulation, if a participant reported the nausea rating of 6 (that is *moderate nausea, want to stop*), then the VR simulation was terminated and the participant was asked to complete the post-exposure SSQ. A score of 6 was assigned for the remaining verbal rating reports.

6.3 Results

Data on nausea ratings, vection ratings and vection duration, SSQ measurements obtained in Experiment 4 passed the test for normal distribution (Appendix D.5). Therefore, parametric statistical analysis was applied for analyzing the data. SAS 8.01 and SPSS 11.0 were used to analyze the data.

6.3.1 Results on nausea ratings

The mean of nausea ratings reported from participants exposed to VR simulation with different navigation velocities in yaw were shown in Figure 6.2. Data are plotted in function of exposure duration as well. This figure illustrated the over all nausea ratings changing over exposure time as well as different navigation velocities in yaw. Nausea ratings increased with increasing exposure time up to around 20 or 25 minutes. When oscillating at 38.2deg/sec, subjects reported highest levels of nausea ratings, while subjects reported lowest levels of nausea ratings at 7.6deg/sec.

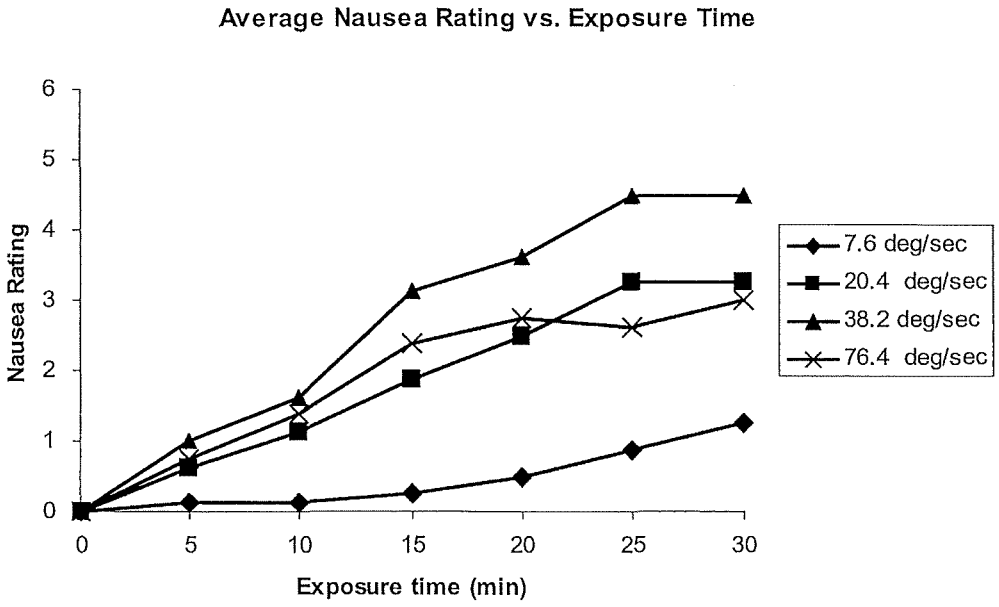

Figure 6.2 The mean of nausea ratings reported from participants exposed to VR simulation with different navigation velocities in yaw. Data are plotted in function of exposure duration. Each data point represents average data of 8 participants.

One ANOVA on nausea ratings were performed to study the effects of navigation velocity in yaw, gender and duration. Navigation velocity, duration of exposure and gender, were found to have significant effects on nausea ratings ($p<0.05$). Meanwhile, the interaction between navigation velocity and gender showed significant effects on nausea ratings ($p<0.05$).

Table 6.1. ANOVA table on nausea ratings analyzing the effects of gender, exposure duration, and navigation conditions for a 30 min VR simulation.

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	137.50	45.83	14.67	<0.01
Gender	1	27.16	27.16	8.69	<0.01
Velocity*Gender	3	25.34	8.45	2.70	0.04
Duration	6	250.69	41.78	13.37	<0.01
Velocity*Duration	18	51.19	2.84	0.91	0.58
Gender*Duration	6	6.15	1.03	0.33	0.92
Velocity*Gender*Duration	18	11.85	0.66	0.21	1.00
Error	168	525.00	3.13	2.97	
Total	223	1034.86			

Multiple comparison analysis using SNK tests of the ANOVA results in Table 6.1 were shown in Table 6.2. It confirmed that nausea ratings were significantly different among four rotating velocities in yaw ($p<0.01$), i.e., nausea ratings significantly increased with increasing navigation velocity from 7.4deg/sec to 38.2deg/sec, peaked

at to 38.2deg/sec and then significantly decreased at 76.4deg/sec. After 5 minutes of VR simulation exposure, nausea rating significantly ($p<0.01$) increased with exposure duration up to 15 minutes, later on, the effects were not significantly different. At the meanwhile, female subjects reported significantly higher nausea rating than male subjects($p<0.01$).

Table 6.2. Student-Newman-Kuels (SNK) tests indicating the effects of (a) navigation conditions, (b) duration, and (c) gender on nausea ratings for a 30 min VR simulation in Experiment 4

(a) SNK groupings on the effects of navigation velocity

SNK Grouping	Nausea Rating	Number	Velocity
A	2.6	56	38.2deg/sec
B	1.8	56	20.4deg/sec
B	1.8	56	76.4deg/sec
C	0.4	56	7.4deg/sec

(b) SNK groupings on the effects of duration

SNK Grouping		Nausea Rating	Number	Duration (min)
	A	3.0	32	30
	A	2.8	32	25
	A	2.3	32	20
B	A	1.9	32	15
B	C	1.1	32	10
D	C	0.6	32	5
D		0.0	32	0

(c) SNK groupings on the effects of gender

SNK Grouping	Nausea Rating	Number	Gender
A	2.03	112	female
B	1.33	112	male

Since ANOVA table 6.1 indicated that the interaction effect between gender and navigation velocity in yaw was also significant, figure 6.3 described the interaction plot of gender and navigation velocity on nausea rating in Experiment 4. From this figure, obviously, the significant interaction effect was possibly because male subjects reported higher nausea rating at 7.4deg/sec than female subjects (with mean of 0.57 reported from male subject and 0.32 reported from female subject) while males reported lower nausea ratings at other navigation velocities than female subjects. However, both two curves depicted similar patterns. It was reasonable to believe that the main effects of navigation velocity on level of nausea rating was robust both applied for male and female subjects.

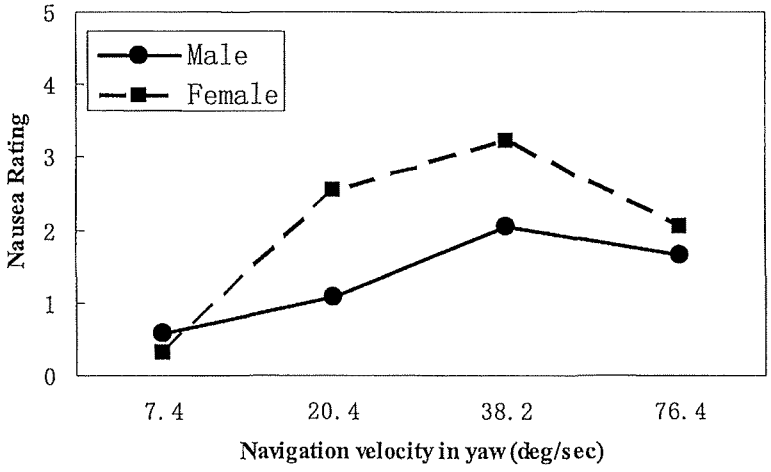

Figure 6.3 Interaction plot of gender and navigation velocity on nausea rating in Experiment 4.

Figure 6.4 indicated the mean of nausea ratings with standard deviation reported from participants at the end of 30-min VR simulation with different navigation velocities in yaw. After 30 minutes VE exposure, subjects reported significantly different strength of nausea symptoms at different navigation conditions, i.e., a nonlinear relationship between navigation velocities in yaw and nausea ratings was identified. This pattern was quite similar as what found in Experiment 2 and 3, i.e., nausea rating significantly increased with increasing navigation velocities up to a certain level, and then nausea rating significantly decreased. Whatever scene movements were presented in fore-and-aft, lateral or yaw in VEs, it seemed there existed nonlinear relationship between navigation velocities and nausea symptoms.

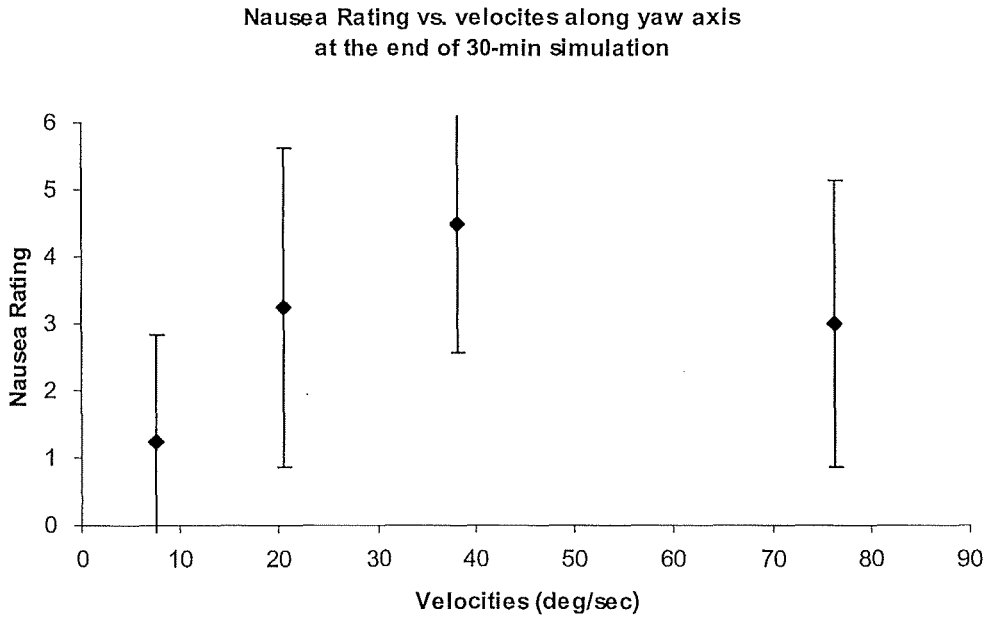

Figure 6.4 The mean of nausea ratings with standard deviation reported from participants at the end of 30-min VR simulation with different navigation velocities

in yaw. Data are plotted in function of velocities. Each data point represents average data of 8 participants.

6.3.2 Vection rating and vection duration

The mean of vection ratings reported from participants exposed to VR simulation with different navigation velocities in yaw were shown in Figure 6.5. Inspection on this figure showed that vection rating increased for the first 10 minutes, after that, the changes in vection ratings became flat. Table 6.3 showed the ANOVA test results of the effects of gender, exposure duration and navigation velocities on vection ratings. Exposure duration, navigation velocity were found significantly affecting the vection ratings ($p<0.05$). However, Student-Newman-Keuls test results shown in Table 6.4 indicated that vection ratings were not significantly different among 10, 20 or 30 minutes exposure. Table 6.4 also indicated that vection ratings were significantly higher when navigation velocity was 76.4deg/sec, 38.2deg/sec and 20.4deg/sec than navigation velocity at 7.6deg/sec.

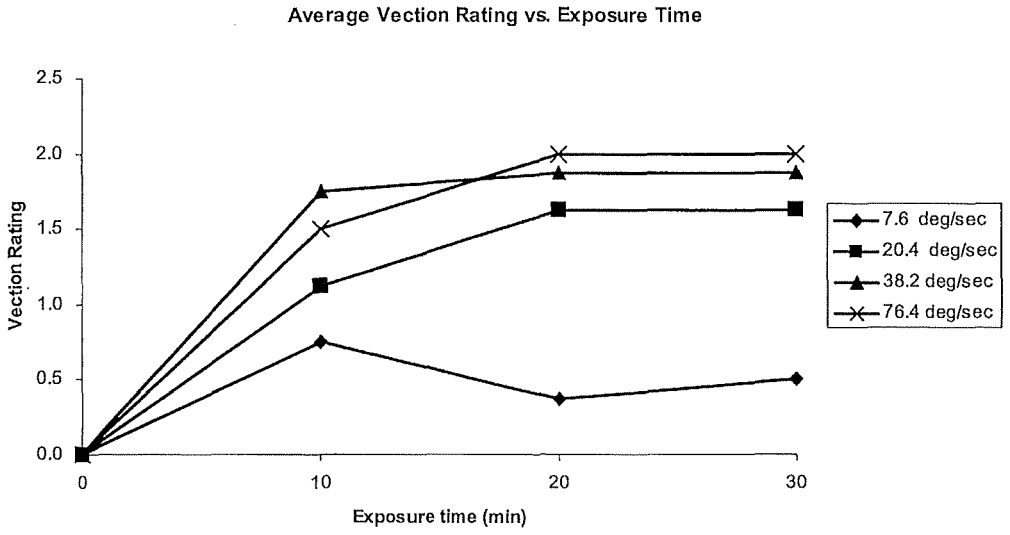

Figure 6.5 The mean of vection ratings reported from participants exposed to VR simulation with different navigation velocities in yaw. Data are plotted in function of exposure duration. Each data point represents average data of 8 participants.

Table 6.3 ANOVA table on vection ratings analyzing the effects of gender, exposure duration, and navigation conditions for a 30 min VR simulation in Experiment 4.

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	20.06	6.69	12.71	<0.01
Gender	1	1.53	1.53	2.91	0.09
Duration	3	49.06	16.35	31.09	<0.01
Velocity*Gender	3	1.41	0.47	0.89	0.75
Velocity*Duration	9	9.13	1.01	1.93	0.06
Gender*Duration	3	0.66	0.22	0.42	0.75
Velocity*Gender*Duration	9	1.16	0.13	0.24	0.99
Error	96	50.50	0.53		
Total	127	133.50			

Table 6.4 Student-Newman-Kuels (SNK) tests indicating the effects of (a) navigation conditions, (b) duration on vection ratings for a 30 min VR simulation in Experiment 4

(a) SNK groupings on the effects of navigation velocity

SNK	Vection Rating	Number	Velocity
A	1.38	32	38.2deg/sec
A	1.38	32	76.4deg/sec
A	1.09	32	20.4deg/sec
B	0.41	32	7.6deg/sec

(b) SNK groupings on the effects of duration

SNK Grouping	Vection Rating	Number	Duration (min)
A	1.50	32	30
A	1.47	32	20
A	1.28	32	10
B	0.00	32	0

Figure 6.6 showed the vection duration as a function of 4 levels of navigation velocities. It showed vection duration increased with increasing navigation velocity. However, the rate of increasing was higher from 7.6deg/sec to 20.4deg/sec, while the rate of increasing was much flatter when navigation velocities were larger than 20.4deg/sec. Table 6.5 showed the ANOVA test results of the effects of gender, and navigation velocities on vection duration, indicating no significant difference among four levels of vection duration. Although, the difference was not significant, we still can see a nonlinear trend, vection duration increased with increasing navigation velocity up to a certain level, after that the effect stabilized.

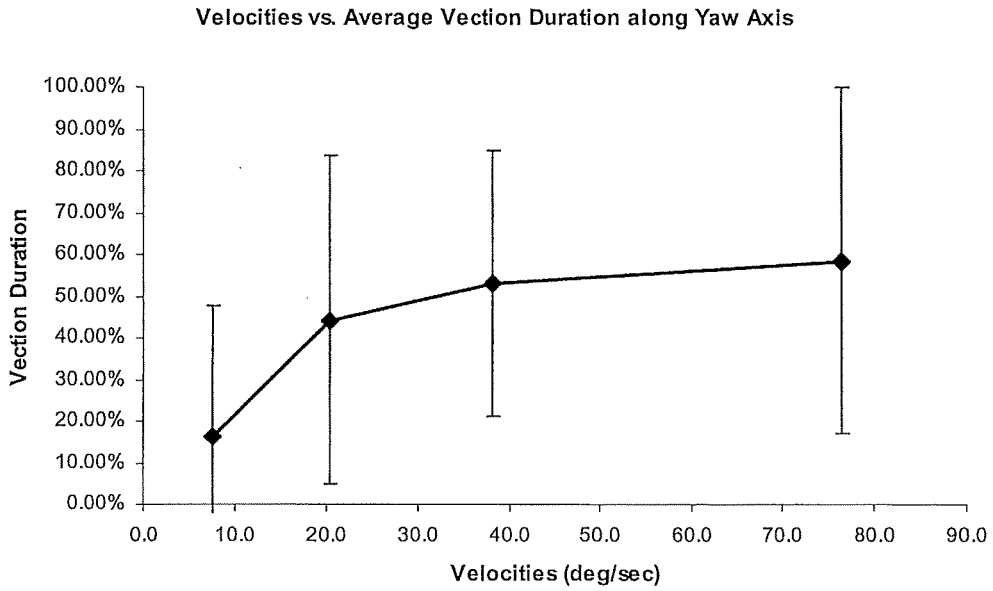

Figure 6.6 The mean of vection duration with standard deviation reported from participants during 30-min VR simulation with different navigation velocities in yaw. Data are plotted in function of velocities. Each data point represents average data of 8 participants

Table 6.5 ANOVA table on vection duration analyzing the effects of gender, and navigation velocities for a 30 min VR simulation in Experiment 4

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	0.84	0.28	2.39	0.09
Gender	1	0.02	0.02	0.15	0.71
Velocity*Gender	3	0.66	0.22	1.87	0.16
Error	24	2.80	0.12		
Total	31	4.13			

6.3.3 Simulator Sickness Questionnaire scores

Figure 6.7 showed the mean of increased SSQ scores reported from participants after exposure of 30-min VR simulation with different navigation velocities in yaw. Data are plotted in function of velocity. Each data point represents average data of 8 participants. Table 6.7 showed the ANOVA results of the effects of gender and navigation velocities on the four SSQ scores. Gender didn't show any significant effect on all the SSQ scores ($p>0.05$). Navigation velocity had significant effects on SSQ nausea score ($p<0.05$). Further SNK results showed that subjects reported significantly higher SSQ nausea scores with navigation velocity at 38.2deg/sec than navigation velocity at 7.6deg/sec. These results indicated similar patterns with what was found on nausea rating.

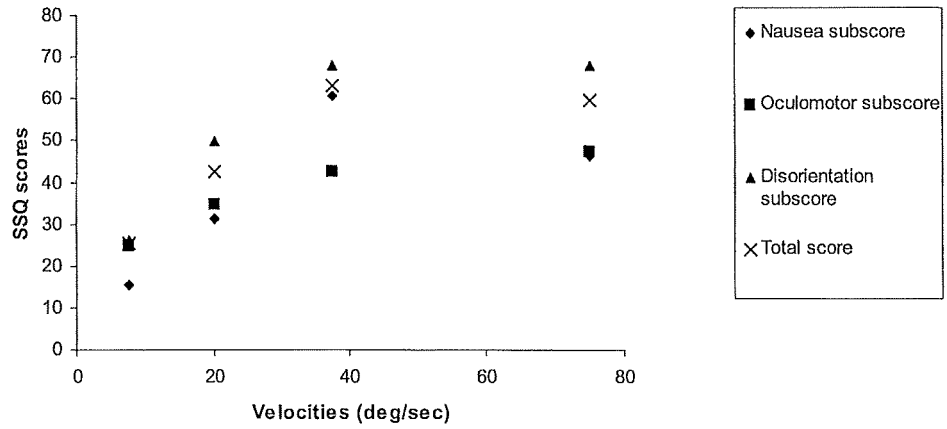

Figure 6.7 The mean of increased SSQ scores reported from participants after exposure of 30-min VR simulation with different navigation velocities in yaw. Data

are plotted in function of velocity. Each data point represents average data of 8 participants.

Table 6.6 ANOVA table on SSQ scores analyzing the effects of gender, and navigation velocities for a 30 min VR simulation in Experiment 4

a) Dependent variable: Nausea subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	9476.58	3158.86	2.83	0.04
Gender	1	1638.21	1638.21	1.42	0.25
Velocity*Gender	3	2889.62	963.21	0.83	0.49
Error	24	27758.54	1156.61		
Total	31	41762.95			

b) Dependent variable: Oculomotor subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	2477.81	825.94	1.07	0.38
Gender	1	1615.96	1615.96	2.09	0.16
Velocity*Gender	3	1070.13	356.71	0.46	0.71
Error	24	18558.42	773.27		
Total	31	23722.31			

c) Dependent variable: Disorientation subscore

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	9131.24	3043.75	1.36	0.28
Gender	1	4747.28	4747.28	2.13	0.16
Velocity*Gender	3	4989.48	1663.17	0.75	0.54
Error	24	53576.40	2232.35		
Total	31	72444.41			

d) Dependent variable: Total score

Source	DF	Sum of Squares	Mean Square	F Value	Pr>F
Velocity	3	7520.08	2506.69	1.87	0.16
Gender	1	2939.14	2939.14	2.19	0.15
Velocity*Gender	3	2512.52	837.51	0.62	0.61
Error	24	32206.45	1341.94		
Total	31	45178.20			

Table 6.7 Student-Newman-Kuels (SNK) tests indicating the effects of navigation velocity on nausea subscore of a 30 min VR simulation in Experiment 4

SNK Grouping		Nausea Subcore	Number	Velocity
	A	60.82	8	38.2deg/sec
B	A	45.32	8	76.4deg/sec
B	A	40.55	8	20.4deg/sec
B		13.12	8	7.6deg/sec

Figure 6.8 and Figure 6.9 showed the mean of increased SSQ nausea subscore / total score with standard deviation reported from participants after exposure of 30-min VR simulation with different navigation velocities in yaw. Similar trends with increasing

rotating velocities in yaw could be found both in nausea subscore and total score from the two figures.

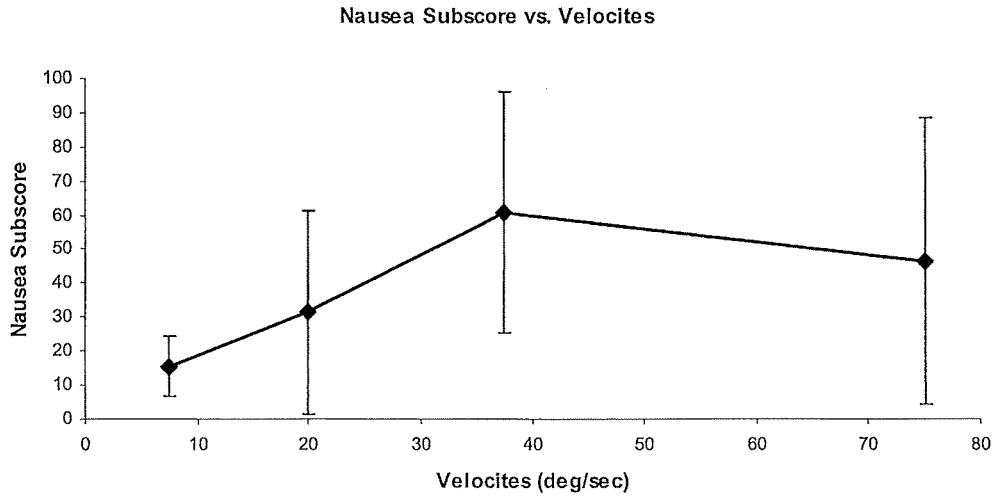

Figure 6.8 The mean of increased SSQ nausea subscore with standard deviation reported from participants after exposure of 30-min VR simulation with different navigation velocities in yaw. Data are plotted in function of velocity. Each data point represents average data of 8 participants.

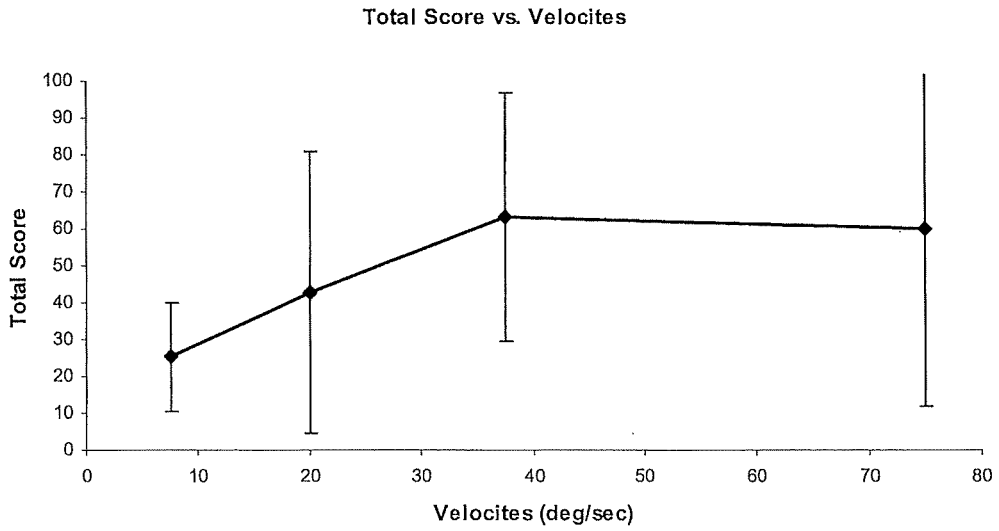

Figure 6.9 The mean of increased SSQ total score with standard deviation reported from participants after exposure of 30-min VR simulation with different navigation velocities in yaw. Data are plotted in function of velocity. Each data point represents average data of 8 participants.

6.4 Discussion

6.4.1 Effects of navigation velocity

Results obtained from this experiment indicated that average nausea ratings during 30 minutes VR simulations significantly ($p<0.05$) increased from 0.4 to 2.6 with increasing navigation velocity in yaw axis from 7.6deg/sec up to 38.2deg/sec, and then average nausea ratings significantly ($p<0.05$) decrease to 1.8 when rotating velocity at 76.4deg/sec. Agree with nausea ratings, subjects also reported significantly higher increased SSQ nausea subscores when navigating at 38.2deg/sec than at 7.6deg/sec.

Results obtained from this study also indicated that subjects reported significantly higher vection ratings when they experienced yaw velocities higher than 7.6deg/sec, although among those three navigation conditions, i.e., 20.4deg/sec, 38.2deg/sec and 79.4deg/sec, subjects didn't show any significant difference. However, subjects didn't reported significantly different levels of vection duration among four

experiment conditions. Nevertheless, results from this experiment confirmed higher levels of vection possibly caused higher levels of cybersickness associated with VR simulations.

6.4.2 Effects of duration

Virtually rotated in yaw in VR simulation could significantly produce cybersickness. After 5 minutes exposure, nausea ratings increased with exposure time up to 15 minutes, after that, the effects stabilized. Vection ratings increased for the first 10 minutes, and became statistically the same for the next 20 minutes. These results quite were quite consistent with the patterns we found from the studies of navigation in fore-and-aft and lateral.

6.4.3 Effects of gender

Results from this experiment showed female significantly reported higher nausea ratings when experienced scene movements oscillation in yaw axis than male ($p<0.01$). However, subjects didn't show any significance difference on vection ratings, vection duration and SSQ scores. Whether female are more sensitive to yaw scene movements in VR simulations than male need to be further studied. At least, it can not be concluded that gender showed strong significant difference on levels of cybersickness from this experiment.

6.4.4 Correlations between dependent variables

Correlations between nausea ratings, vection ratings, vection duration and SSQ scores obtained at the end of 30 min VR simulation in Experiment 4 were shown in Table 6.8. From this table, correlations between vection duration and nausea ratings, SSQ scores were not significantly correlated, however correlations between other dependent variables were significantly correlated ($p<0.05$). As we have reported, the different patterns on vection ratings and vection duration were consistent with a literature by Flanagan et al., 2002.

Table 6.8 Correlations between nausea ratings, vection ratings, vection durations and SSQ scores at the end of 30 min VR simulation in Experiment 4

		Nausea Rating	Vection Rating	Vection Duration	SSQ_NS	SSQ_OS	SSQ_DS	SSQ_TS
Nausea Rating	Pearson Correlation	1.00	0.53**	0.11	0.77**	0.40*	0.65**	0.65**
	Sig.		<0.01	0.57	<0.01	0.02	<0.01	<0.01
Vection Rating	Pearson Correlation		1.00	0.50**	0.67**	0.41**	0.61**	0.60**
	Sig.			<0.01	<0.01	0.02	<0.01	<0.01
Vection Duration	Pearson Correlation			1.00	0.20	0.14	0.16	0.18
	Sig.				0.28	0.44	0.37	0.32
SSQ_NS	Pearson Correlation				1.00	0.71**	0.93**	0.94**
	Sig.					<0.01	<0.01	<0.01
SSQ_OS	Pearson Correlation					1.00	0.80**	0.90**
	Sig.						<0.01	<0.01
SSQ_DS	Pearson Correlation						1.00	0.97**
	Sig.							<0.01
SSQ_TS	Pearson Correlation							1.00
	Sig.							

* Correlation is significant at the 0.05 level

** Correlation is significant at the 0.01 level

6.4.5 Comparing results of previous studies

Apart from cybersickness, visually induced motion sickness provocated by rotating drum is another close research field. Hu et al.'s study (1989) reported a curvilinear relationship between speed of drum rotation and severity of symptoms of motion sickness. Figure 6.10 showed the combined graph with the results from this study and Hu et al.'s study.

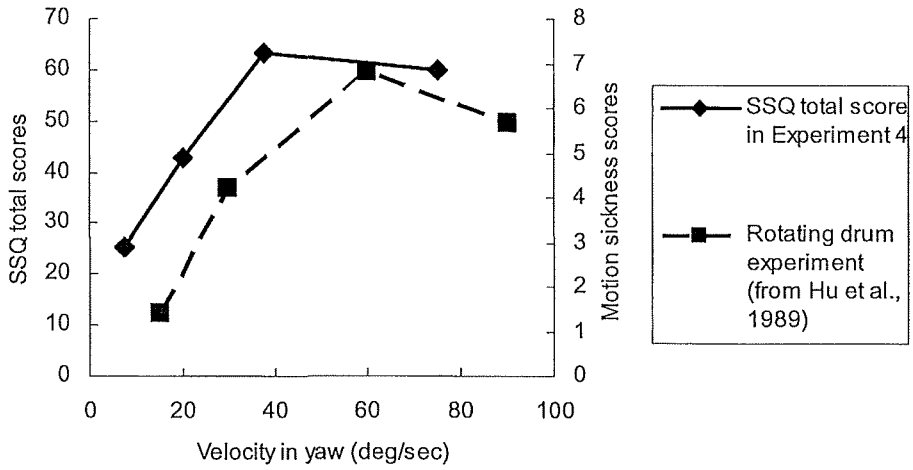

Figure 6.10 Comparison of sickness level in rotating drum experiment from Hu et al., 1989 and Experiment 4.

These two curves shared a similar pattern, increased with increasing velocity up to a certain level, and then stabilized or dropped a little bit, although they didn't coincide

totally. This difference may be explained by the role of spatial frequency since scene complexity should also have an effect on cybersickness. In these two experiments, average spatial frequencies of VEs were different. In Experiment 4, the average spatial frequencies was 0.116cpd and SSQ total score peaked at SV=4.408 cycle/sec; while in Hu's experiment, the average spatial frequencies was 0.067cpd and motion sickness score peaked at SV=4.02 cycle/sec. Explained by SV, the results from these two experiments quite agreed.

On the other hand, we have pointed out, in Experiment 3 and Experiment 4, the navigation path were both presented in sinusoidal wave movements, although the former was presented in lateral and the latter was presented in yaw. The frequencies in sinusoidal wave in both two experiments were corresponding. In Experiment 3, the average spatial frequency of the VE was 0.097cpd which was close to that in Experiment 4, i.e., 0.116cpd. We make a combined graph on the SSQ total score results obtained from Experiment 3 and Experiment 4 in Figure 6.11. The two curves shared the similar pattern.

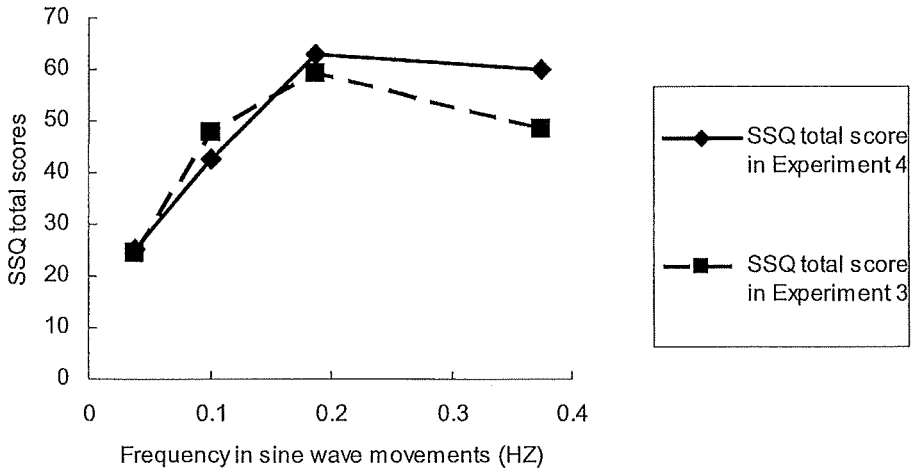

Figure 6.11 Comparison of SSQ total scores in Experiment 3 and Experiment 4.

Chapter 7 Conclusions and Implications

7.1 Summary of findings

7.1.1 Findings from Experiment 1a & 1b

Results from Experiment 1a & 1b indicate that the presence of scene movements along any one of the three translational axes (i.e., fore-and-aft, lateral and vertical) during a virtual reality (VR) simulation can significantly increase the levels of nausea ($p<0.05$) and SSQ scores (Total SSQ score: $p<0.05$) among VE users. Participants experienced significant increases in levels of nausea rating ($p<0.01$) after navigating the VE along a translational axis for 10 minutes or longer. Strong correlation relationships between vection ratings and nausea ratings were found ($p<0.05$). This suggests that cybersickness is a type of vection induced motion sickness.

The presence of translational navigation in a VE along different axes was found to cause different levels of cybersickness on the viewers. The levels of nausea rating associated with scene movements in the lateral axis was the highest followed by vertical axis and fore-and-aft axis ($p<0.01$). Lateral or vertical navigation produced significant ($p<0.05$) higher SSQ scores than control condition, while the SSQ scores produced by fore-and-aft navigation were not significantly different from control

condition ($p>0.05$). These suggest that navigating along lateral or vertical axes in a VE may contribute to higher levels of sickness than navigation along the fore-and-aft axis.

7.1.2 Findings from Experiment 2

The investigation of effects of different levels of navigation velocities in fore-and-aft on level of cybersickness is repeated and extended to 150m/sec using a different VE compared with a previous study (So et al., 2001b). Results from Experiment 2 indicate that participants experienced significant increases in levels of nausea rating ($p<0.05$) and vection rating ($p<0.05$) after navigating the VE in fore-and-aft axis for 10 minutes or longer. The presence of scene movements in fore-and-aft with different levels of navigation velocities can cause significantly different levels of nausea ratings ($p<0.05$), vection ratings ($p<0.05$), vection duration ($p<0.05$) and SSQ nausea scores ($p<0.05$) among VE users. A nonlinear relationship was found between the different navigation velocities in fore-and-aft and rated level of cybersickness. Nausea ratings increased with increasing navigation velocity in fore-and-aft axis from 3m/sec up to 30m/sec, significantly decreased at 60m/sec, and then became statistically the same at 150m/sec. Furthermore, subjects reported significantly higher vection duration and SSQ nausea scores at 30m/sec than 3m/sec.

Comparing with a previous study conducted by So et al. (2001b), both two studies indicated nonlinear effects of navigation velocities in fore-and-aft on cybersickness. Although, the two curves peaked at different velocity levels, considering the effects of spatial frequencies across different VEs, the results from two studies actually quite agree with each other.

It was also found that the effects of navigation velocities on vection duration showed a similar pattern as the effects of navigation velocities on nausea ratings. This result indicates that vection duration could be an important indicator for measuring vection in VEs since it presented close relationship with nausea symptoms.

7.1.3 Findings from Experiment 3

Effects of different levels of navigation velocities in lateral on level of cybersickness are investigated. Results from Experiment 3 indicate that participants experienced significant increases in levels of nausea rating ($p<0.05$) and vection rating ($p<0.05$) after navigating the VE in lateral for 10 minutes or longer. The presence of scene movements in lateral with different levels of navigation velocities can cause significantly different levels of nausea ($p<0.05$) and SSQ scores (i.e., SSQ total score and SSQ nausea score, $p<0.05$) among users. A nonlinear relationship between navigation velocities in lateral and levels of cybersickness were identified. Nausea ratings increased significantly with increasing navigation velocity in lateral axis from

3m/sec up to 15m/sec, and then significantly decreased at 30m/sec. Nausea ratings peaked at 15m/sec and touched bottom at 3m/sec. The patterns found on SSQ scores were consistent with the findings on nausea ratings. Significantly higher SSQ nausea score and SSQ total score ($p<0.05$) are reported with lateral navigation at 15m/sec than those with lateral navigation at 3m/sec. Meanwhile, subjects reported significantly ($p<0.05$) higher vection rating at 15m/sec, which confirms the strong correlations between nausea symptom and vection strength.

7.1.4 Findings from Experiment 4

Effects of different levels of navigation velocities in lateral on level of cybersickness are investigated. Results from Experiment 4 indicate that participants experienced significant increases in levels of nausea rating ($p<0.05$) and vection rating ($p<0.05$) after rotating in VE in yaw axis for 10 minutes or longer. The presence of scene movements in yaw with different rotating speeds can cause significantly different level of cybersickness nausea ratings ($p<0.01$), vection ratings ($p<0.05$) and SSQ nausea scores ($p<0.05$) among VE users. Similar to the findings in Experiment 2 and Experiment 3, a nonlinear relationship between navigation velocities in yaw and level of cybersickness was identified. Nausea ratings increase with increasing navigation velocities in yaw from 7.6deg/sec up to 38.2deg/sec (peaked at 38.2 deg/sec, $p<0.05$), and then significantly decreased at 76.4deg/sec. Similar patterns

were found on the results of SSQ scores. Subjects reported significantly ($p<0.05$) higher SSQ nausea scores at 38.2deg/sec than at 7.6deg/sec.

Comparing a study conducted by Hu et al. in 1989 where rotating drum was used to produce visually induced motion sickness, the results from this study agree with the findings in Hu's study. Both studies indicated nonlinear relationships between velocities in yaw and severity of motion sickness.

7.2 Conclusions and implications of this study

Exposure to VR simulation can cause cybersickness and approximately more than 80% percentage of the users report some level of discomfort after VR simulation, therefore, it is critical to investigate the problem of cybersickness. As supported by literature (Hettingder, 1992; Kennedy et al., 1996; McCauely & Sharkey, 1992), cybersickness is believed as a type of visually induced motion sickness hence visual scene movements in VEs play an important role in producing cybersickness. In this study, the relationships between scene movements and levels of cybersickness are investigated. In particular, the role of navigation velocities in different axes through a VE on level of cybersickness is examined. Four experiments were conducted to explore the effects of navigation velocities in different axes in VR simulations. Due to limitations in resources, the effects of navigation velocities have been studied in only three axes of navigation, i.e., fore-and-aft, lateral and yaw axes.

Experiment 1 is a complement study of Lo and So's study in 2001. Experiment 1 studied the effects of scene movements along three translational axes (i.e., fore-and-aft, lateral, vertical) while navigating in a VE on the levels of cybersickness. Results indicated that navigations in all three translational axes could significantly increase the level of cybersickness ($p<0.01$). Navigating along lateral or vertical axes in VEs could produce higher sickness level compared with navigating along fore-and-aft axis. Since subjects reported significantly highest nausea ratings and vection ratings in lateral navigation, later experiments would focus on the effects of navigation velocities in the fore-and-aft axis and lateral axis.

Experiment 2 studied the effects of navigation velocities in fore-and-aft on level of cybersickness up to 150m/sec. Significant main effects on levels of cybersickness were found ($p<0.01$). The result is consistent with an earlier study in which viewers navigated in a VE in a multi-axes path with a dominant motion along fore-and-aft axis. In particular, the nonlinear relationship between navigation velocities in the fore-and-aft axis and levels of nausea ratings are found to be consistent. This finding is important because two reasons: firstly, the present study is the first study that has isolated the navigation motion to only fore-and-aft axis. Secondly, the results were found to be consistent with a previous related (but not the same) study. This suggests a high general validity.

Effects of navigation velocities in lateral from 3m/sec to 30m/sec on level of cybersickness were investigated. A significant main effect of navigation velocities on level of cybersickness ($p<0.01$) were found. This study indicated a nonlinear relationship between navigation velocities in lateral and level of cybersickness. This pattern is consistent with what have been found in Experiment 2 while navigating in fore-and-aft. This may suggest that the influences of scene movements in different axes on the levels of cybersickness share the similar mechanisms.

Effects of navigation velocities in yaw ranged from 7.4deg/sec to 76.4deg/sec on level of cybersickness were investigated. Similar to the findings in Experiments 2 and 3, a significant main effect of navigation velocities on level of cybersickness ($p<0.01$) were identified. A nonlinear relationship between navigation velocities in yaw and level of cybersickness was identified. This finding was consistent with a previous related study which reported a curvilinear relationship between speed of drum rotation and severity of visually induced motion sickness.

In summary, it is concluded that navigating inside a VE in any of motion axes can significantly increase the level of cybersickness. The patterns of effects of navigation velocities associated with scene movements in fore-and-aft, lateral and yaw axes on the level of cybersickness are similar. Different levels of navigation velocities can cause significantly different levels of cybersickness with a nonlinear relationship. The results of this study can help VR engineers customize a VE by taking into

consideration the accepted level of cybersickness so that the feeling of presence and discomfort can be balanced. This is important to design of VR consumer products, use of VR for command and control, and for training process.

Moreover, navigation velocity has been defined as one of the important component in Spatial Velocity. The results from this research contribute to the development of Cybersickness Dose Value (CSDV) introduced by So et al. (2001a), which is a formulation for predicting the level of cybersickness in VEs.

Chapter 8 Limitations and future work

According to sensory rearrangement theory, visual and vestibular systems are the two key input systems associated with the development of cybersickness. In this study, we focus on the role of visual stimuli and control another important sensory source -vestibular stimuli, i.e., no physical movement was considered in the study. Other visual influencing factors, e.g., field-of-view, are also controlled and limited to 36deg*48 deg.

On data sample, Stern et al. (1993) reported that Chinese subjects showed significantly greater disturbances in gastric activity and higher level of sickness symptoms compared with European-American, and African-American subjects by when exposed to rotating drum. This motivated us used Chinese participants as subjects in this study. However, due to resources limitation, only HKUST students or staff aged from 18 to 40 participated in the experiments. In another word, in current stage, the results from this study can only applied to the limited VE user populations. For example, if pilots with abundant flight experiences were used as subjects, the effects of navigating in different motion axes may not similar as we found in this study since pilots get used to vertical motion as normal people don't.

In Experiment 1, sine-wave oscillation movements were used as presenting the navigation motion and only one r.m.s velocity (15m/sec) was used in each condition.

Furthermore, in Experiment 2 to Experiment 4, different levels of navigation velocities were investigated in fore-and-aft axis (with velocity range from 3m/sec to 150m/sec), lateral axis (with velocity range from 3m/sec to 30m/sec) and yaw axis (with velocity range from 7.6deg/sec to 76.4deg/sec). Future studies to fully explore the effects of scene movements in different motion axes could extend to vertical, pitch and roll axes. Since only limited velocity ranges were considered in this study, especially in Experiment 3 and Experiment 4, future study may consider to extend the navigation velocity range to further verify the nonlinear relationships between navigation velocities and levels of cybersickness. In addition, Yuen's study (2002) showed that an increase in scene complexity would lead to increase in levels of cybersickness until spatial frequency of about 0.076cpd is reached. It is meaningful and important to consider the effects of interaction between navigation velocity and scene complexity in the future study.

Moreover, by using sine wave oscillation scene movements, the effects of navigation velocities and motion frequencies were confounding. We manipulated the navigation velocities by manipulating the motion frequencies with amplitude controlled to be one certain level. However, navigation velocities can also be manipulated by varying different levels of amplitudes.

Root mean square value of navigation velocity and average spatial frequency are used to represent the scene complexity of the VE. The methods of analyzing the

navigation velocity should also be improved, for example, to use a contiguous velocity function to replace the r.m.s value is beneficial since it provides more accurate information on the velocity profile.

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Appendix A The definitions of the 7-point nausea rating

(adapted from Golding & Kerguelen, 1992)

Rating	Definition
0	No symptoms
1	Any unpleasant symptoms ,however slight
2	Mild unpleasant symptoms, e.g. stomach awareness, sweating but no nausea
3	Mild nausea
4	Mild to moderate nausea
5	Moderate nausea but can continue
6	Moderate nausea, want to stop

Appendix B The calculations in the Simulator Sickness Questionnaire (adapted from Kennedy & Lane, 1993)

None = 0

Slight = 1

Moderate = 2

Severe = 3

Symptoms	Weights for 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

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

Appendix C The definitions of the 4-point vection rating

(adapted from Hettinger et al., 1990)

Rating	Definition
0	No feeling of self-motion
1	Slightly feeling of self-motion
2	Moderate feeling of self-motion
3	Strong feeling of self-motion

Appendix D Tests for normal distribution for the data collected in the Experiments

D.1 Tests for normal distribution on data collected in Experiment 1a

D.1.1 Results on nausea ratings

One-Sample Kolmogorov-Smirnov Test (Condition: fore-and-aft)

		5min	10min	15min	20min	25min	30min
N		16	16	16	16	16	16
Normal Parameters[a,b]	Mean	.1250	.5625	.7500	1.0625	1.4375	1.5625
	Std. Deviation	.34157	.96393	.77460	1.06262	1.26326	1.36473
Most Extreme Differences	Absolute	.518	.408	.271	.273	.185	.186
	Positive	.518	.408	.271	.273	.185	.186
	Negative	-.357	-.280	-.189	-.164	-.172	-.166
Kolmogorov-Smirnov Z		2.071	1.631	1.084	1.094	.740	.746
Asymp. Sig. (2-tailed)		.001	.010	.190	.183	.645	.635

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: lateral)

		5min	10min	15min	20min	25min	30min
N		16	16	16	16	16	16
Normal Parameters[a,b]	Mean	.2500	1.1250	1.8125	2.2500	2.6250	2.8125
	Std. Deviation	.44721	1.66833	2.00728	1.94936	2.02896	2.16699
Most Extreme Differences	Absolute	.462	.280	.345	.239	.183	.146
	Positive	.462	.280	.345	.239	.183	.146
	Negative	-.288	-.250	-.183	-.124	-.126	-.117
Kolmogorov-Smirnov Z		1.848	1.119	1.379	.954	.734	.585
Asymp. Sig. (2-tailed)		.002	.163	.053	.322	.654	.884

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: verticall)

		5min	10min	15min	20min	25min	30min
N		16	16	16	16	16	16
Normal Parameters[a,b]	Mean	.3125	.6875	1.0000	1.6250	1.9375	2.1875
	Std. Deviation	.47871	.70415	1.03280	1.20416	1.34009	1.51520
Most Extreme Differences	Absolute	.431	.273	.271	.253	.231	.237
	Positive	.431	.273	.271	.253	.231	.237
	Negative	-.257	-.234	-.209	-.177	-.144	-.138
Kolmogorov-Smirnov Z		1.722	1.092	1.084	1.011	.926	.947
Asymp. Sig. (2-tailed)		.005	.184	.190	.258	.358	.331

a. Test distribution is Normal.

b. Calculated from data.

D.1.2 Results on vection ratings

One-Sample Kolmogorov-Smirnov Test (Condition: fore-and-aft)

		5min	10min	15min	20min	25min	30min
N		16	16	16	16	16	16
Normal Parameters[a,b]	Mean	.6250	1.0000	1.1875	1.1875	1.3125	1.3125
	Std. Deviation	.95743	.89443	1.04682	1.04682	1.13835	1.13835
Most Extreme Differences	Absolute	.368	.250	.196	.196	.188	.188
	Positive	.368	.250	.196	.196	.188	.188
	Negative	-.257	-.188	-.156	-.156	-.165	-.165
Kolmogorov-Smirnov Z		1.472	1.000	.784	.784	.752	.752
Asymp. Sig. (2-tailed)		.052	.270	.570	.570	.624	.624

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: Lateral)

		5min	10min	15min	20min	25min	30min
N		16	16	16	16	16	16
Normal Parameters[a,b]	Mean	.9375	1.3750	1.4375	1.6250	1.7500	1.7500
	Std. Deviation	.92871	.95743	.96393	.95743	1.06458	1.12546
Most Extreme Differences	Absolute	.223	.215	.220	.215	.197	.247
	Positive	.223	.215	.175	.181	.197	.247
	Negative	-.156	-.181	-.220	-.215	-.192	-.242
Kolmogorov-Smirnov Z		.893	.859	.881	.859	.788	.990
Asymp. Sig. (2-tailed)		.403	.451	.420	.451	.564	.281

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: vertical)

		5min	10min	15min	20min	25min	30min
N		16	16	16	16	16	16
Normal Parameters[a,b]	Mean	.6875	1.0625	1.1875	1.1875	1.2500	1.2500
	Std. Deviation	.70415	.85391	.83417	.83417	.85635	.85635
Most Extreme Differences	Absolute	.273	.279	.276	.276	.240	.240
	Positive	.273	.279	.276	.276	.240	.240
	Negative	-.234	-.221	-.224	-.224	-.198	-.198
Kolmogorov-Smirnov Z		1.092	1.117	1.106	1.106	.959	.959
Asymp. Sig. (2-tailed)		.184	.165	.173	.173	.316	.316

a. Test distribution is Normal.

b. Calculated from data.

D.1.3 Results on SSQ scores

One-Sample Kolmogorov-Smirnov Test (Condition: fore-and-aft)

		NS	OS	DS	TS
N		16	16	16	16
Normal Parameters[a,b]	Mean	10.7325	14.2125	22.6200	17.2975
	Std. Deviation	12.49946	16.57809	27.78194	18.41736
Most Extreme Differences	Absolute	.242	.218	.238	.220
	Positive	.242	.218	.238	.220
	Negative	-.195	-.196	-.208	-.174
Kolmogorov-Smirnov Z		.969	.872	.952	.879
Asymp. Sig. (2-tailed)		.305	.433	.325	.423

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: Lateral)

		NS	OS	DS	TS
N		16	16	16	16
Normal Parameters[a,b]	Mean	26.2350	23.2138	49.5900	35.0625
	Std. Deviation	22.70974	18.86770	43.71523	28.21573
Most Extreme Differences	Absolute	.249	.198	.259	.249
	Positive	.249	.198	.259	.249
	Negative	-.140	-.115	-.145	-.137
Kolmogorov-Smirnov Z		.995	.790	1.034	.994
Asymp. Sig. (2-tailed)		.276	.560	.235	.276

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: Vertical)

		NS	OS	DS	TS
N		16	16	16	16
Normal Parameters[a,b]	Mean	22.0613	35.0575	41.7600	37.1663
	Std. Deviation	30.90700	34.88722	45.74579	38.71021
Most Extreme Differences	Absolute	.291	.200	.182	.174
	Positive	.291	.200	.182	.174
	Negative	-.238	-.157	-.181	-.168
Kolmogorov-Smirnov Z		1.164	.802	.728	.697
Asymp. Sig. (2-tailed)		.133	.541	.664	.716

a. Test distribution is Normal.

b. Calculated from data.

D.2 Tests for normal distribution on data collected in Experiment 1b

D.2.1 Results on nausea ratings

One-Sample Kolmogorov-Smirnov Test (Condition: fore-and-aft)

		5min	10min	15min	20min	25min	30min
N		12	12	12	12	12	12
Normal Parameters[a,b]	Mean	.0833	.5000	.5000	.7500	.7500	.8333
	Std. Deviation	.28868	.52223	.52223	.75378	.96531	1.11464
Most Extreme Differences	Absolute	.530	.331	.331	.257	.365	.356
	Positive	.530	.331	.331	.257	.365	.356
	Negative	-.386	-.331	-.331	-.213	-.236	-.227
Kolmogorov-Smirnov Z		1.837	1.146	1.146	.890	1.263	1.233
Asymp. Sig. (2-tailed)		.002	.145	.145	.407	.082	.096

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: lateral)

		5min	10min	15min	20min	25min	30min
N		12	12	12	12	12	12
Normal Parameters[a,b]	Mean	.0000	.5833	1.0000	1.2500	1.7500	1.7500
	Std. Deviation	.00000[c]	.66856	.95346	1.42223	1.65831	1.91288
Most Extreme Differences	Absolute		.309	.250	.236	.271	.237
	Positive		.309	.250	.236	.271	.237
	Negative		-.233	-.167	-.190	-.191	-.180
Kolmogorov-Smirnov Z			1.069	.866	.819	.939	.819
Asymp. Sig. (2-tailed)			.203	.441	.514	.341	.513

a. Test distribution is Normal.

b. Calculated from data.

c. The distribution has no variance for this variable. One-Sample Kolmogorov-Smirnov Test cannot be performed.

One-Sample Kolmogorov-Smirnov Test (Condition: vertical)

		5min	10min	15min	20min	25min	30min
N		12	12	12	12	12	12
Normal Parameters[a,b]	Mean	.1667	.4167	.6667	.8333	1.0000	1.1667
	Std. Deviation	.38925	.66856	.77850	.93744	1.04447	1.26730
Most Extreme Differences	Absolute	.499	.400	.304	.313	.247	.238
	Positive	.499	.400	.304	.313	.247	.238
	Negative	-.334	-.267	-.196	-.227	-.169	-.179
Kolmogorov-Smirnov Z		1.729	1.386	1.053	1.084	.857	.825
Asymp. Sig. (2-tailed)		.005	.043	.217	.190	.454	.505

a. Test distribution is Normal.

b. Calculated from data.

D.2.2 Results on vection ratings

One-Sample Kolmogorov-Smirnov Test (Condition: fore-and-aft)

		5min	10min	15min	20min	25min	30min
N		12	12	12	12	12	12
Normal Parameters[a,b]	Mean	.1667	.6667	1.0000	1.0833	1.0000	1.0833
	Std. Deviation	.38925	.65134	1.04447	1.08362	1.04447	1.16450
Most Extreme Differences	Absolute	.499	.279	.247	.258	.247	.241
	Positive	.499	.264	.247	.258	.247	.241
	Negative	-.334	-.279	-.169	-.218	-.169	-.176
Kolmogorov-Smirnov Z		1.729	.966	.857	.894	.857	.833
Asymp. Sig. (2-tailed)		.005	.308	.454	.402	.454	.491

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: lateral)

		5min	10min	15min	20min	25min	30min
N		12	12	12	12	12	12
Normal Parameters[a,b]	Mean	.3333	.5000	.5833	.8333	.9167	1.0000
	Std. Deviation	.65134	.67420	.79296	.93744	.90034	1.04447
Most Extreme Differences	Absolute	.446	.354	.352	.313	.262	.247
	Positive	.446	.354	.352	.313	.262	.247
	Negative	-.304	-.229	-.231	-.227	-.219	-.169
Kolmogorov-Smirnov Z		1.544	1.227	1.221	1.084	.909	.857
Asymp. Sig. (2-tailed)		.017	.099	.102	.190	.381	.454

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: vertical)

		5min	10min	15min	20min	25min	30min
N		12	12	12	12	12	12
Normal Parameters[a,b]	Mean	.3333	.6667	1.0000	1.0833	1.0833	1.0833
	Std. Deviation	.49237	.77850	.85280	.90034	.90034	.90034
Most Extreme Differences	Absolute	.417	.304	.213	.262	.262	.262
	Positive	.417	.304	.213	.219	.219	.219
	Negative	-.249	-.196	-.213	-.262	-.262	-.262
Kolmogorov-Smirnov Z		1.446	1.053	.737	.909	.909	.909
Asymp. Sig. (2-tailed)		.031	.217	.648	.381	.381	.381

a. Test distribution is Normal.

b. Calculated from data.

D.2.3 Results on SSQ scores

One-Sample Kolmogorov-Smirnov Test (Condition: fore-and-aft)

		NS	OS	DS	TS
N		24	24	24	24
Normal Parameters[a,b]	Mean	1.9875	6.0008	4.6400	4.9867
	Std. Deviation	4.85564	10.71488	8.86735	8.51900
Most Extreme Differences	Absolute	.492	.379	.450	.346
	Positive	.492	.379	.450	.346
	Negative	-.341	-.288	-.300	-.279
Kolmogorov-Smirnov Z		2.411	1.856	2.203	1.694
Asymp. Sig. (2-tailed)		.000	.002	.000	.006

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: lateral)

		NS	OS	DS	TS
N		24	24	24	24
Normal Parameters[a,b]	Mean	7.1550	11.6858	10.4400	11.3750
	Std. Deviation	16.22166	23.44097	31.86169	26.13290
Most Extreme Differences	Absolute	.337	.320	.378	.332
	Positive	.337	.320	.378	.320
	Negative	-.330	-.309	-.372	-.332
Kolmogorov-Smirnov Z		1.651	1.565	1.854	1.625
Asymp. Sig. (2-tailed)		.009	.015	.002	.010

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: vertical)

		NS	OS	DS	TS
N		24	24	24	24
Normal Parameters[a,b]	Mean	1.1925	6.3167	4.0600	4.8308
	Std. Deviation	4.27800	9.39502	7.65646	7.59931
Most Extreme Differences	Absolute	.526	.291	.452	.349
	Positive	.526	.291	.452	.349
	Negative	-.390	-.251	-.298	-.262
Kolmogorov-Smirnov Z		2.579	1.426	2.215	1.708
Asymp. Sig. (2-tailed)		.000	.034	.000	.006

a. Test distribution is Normal.

b. Calculated from data.

D.3 Tests for normal distribution on data collected in Experiment 2

D.3.1 Results on nausea ratings

One-Sample Kolmogorov-Smirnov Test (Condition: 3m/sec)

		5min	10min	15min	20min	25min	30min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.1250	.1250	.1250	.1250	.2500	.2500
	Std. Deviation	.35355	.35355	.35355	.35355	.46291	.46291
Most Extreme Differences	Absolute	.513	.513	.513	.513	.455	.455
	Positive	.513	.513	.513	.513	.455	.455
	Negative	-.362	-.362	-.362	-.362	-.295	-.295
Kolmogorov-Smirnov Z		1.451	1.451	1.451	1.451	1.288	1.288
Asymp. Sig. (2-tailed)		.050	.050	.050	.050	.072	.072

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: 8m/sec)

		5min	10min	15min	20min	25min	30min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.1250	.1250	.1250	.3750	.6250	.7500
	Std. Deviation	.35355	.35355	.35355	.51755	1.06066	1.16496
Most Extreme Differences	Absolute	.513	.513	.513	.391	.347	.365
	Positive	.513	.513	.513	.391	.347	.365
	Negative	-.362	-.362	-.362	-.261	-.278	-.260
Kolmogorov-Smirnov Z		1.451	1.451	1.451	1.105	.982	1.033
Asymp. Sig. (2-tailed)		.050	.050	.050	.174	.290	.236

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Conditions: 15m/sec)**

		5 min	10 min	15 min	20 min	25 min	30 min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.6250	.7500	.6250	.6250	1.2500	1.5000
	Std. Deviation	1.40789	1.38873	.74402	.74402	.88641	.92582
Most Extreme Differences	Absolute	.421	.330	.300	.300	.361	.205
	Positive	.421	.330	.300	.300	.361	.205
	Negative	-.329	-.295	-.200	-.200	-.264	-.205
Kolmogorov-Smirnov Z		1.192	.935	.847	.847	1.021	.581
Asymp. Sig. (2-tailed)		.117	.347	.469	.469	.248	.888

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Conditions: 30m/sec)**

		5 min	10 min	15 min	20 min	25 min	30 min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.3750	.6250	1.0000	1.7500	2.2500	3.1250
	Std. Deviation	.51755	.51755	.75593	1.16496	1.48805	1.88509
Most Extreme Differences	Absolute	.391	.391	.250	.240	.193	.151
	Positive	.391	.261	.250	.240	.175	.151
	Negative	-.261	-.391	-.250	-.233	-.193	-.150
Kolmogorov-Smirnov Z		1.105	1.105	.707	.679	.546	.428
Asymp. Sig. (2-tailed)		.174	.174	.699	.745	.927	.993

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: 60m/sec)

		5min	10min	15min	20min	25min	30min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.3750	.3750	.6250	1.1250	1.5000	1.6250
	Std. Deviation	.51755	.51755	.91613	1.55265	1.85164	2.06588
Most Extreme Differences	Absolute	.391	.391	.377	.391	.291	.284
	Positive	.391	.391	.377	.391	.291	.284
	Negative	-.261	-.261	-.248	-.261	-.209	-.216
Kolmogorov-Smirnov Z		1.105	1.105	1.068	1.105	.823	.804
Asymp. Sig. (2-tailed)		.174	.174	.204	.174	.507	.538

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: 150m/sec)

		5min	10min	15min	20min	25min	30min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.3750	.7500	1.1250	1.2500	1.3750	1.6250
	Std. Deviation	.51755	.88641	1.12599	1.16496	1.06066	.91613
Most Extreme Differences	Absolute	.391	.301	.216	.240	.222	.284
	Positive	.391	.301	.216	.233	.153	.216
	Negative	-.261	-.199	-.159	-.240	-.222	-.284
Kolmogorov-Smirnov Z		1.105	.852	.611	.679	.628	.803
Asymp. Sig. (2-tailed)		.174	.462	.849	.745	.825	.540

a. Test distribution is Normal.

b. Calculated from data.

D.3.2 Results on vection ratings

One-Sample Kolmogorov-Smirnov Test **(Conditions: 3m/sec)**

		10 min	20 min	30 min
N		8	8	8
Normal Parameters[a,b]	Mean	.6250	.7500	1.0000
	Std. Deviation	.51755	.46291	.75593
Most Extreme Differences	Absolute	.391	.455	.250
	Positive	.261	.295	.250
	Negative	-.391	-.455	-.250
Kolmogorov-Smirnov Z		1.105	1.288	.707
Asymp. Sig. (2-tailed)		.174	.072	.699

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition 8m/sec)

		10min	20min	30min
N		8	8	8
Normal Parameters[a,b]	Mean	1.1250	1.2500	.6250
	Std. Deviation	.64087	1.03510	.91613
Most Extreme Differences	Absolute	.327	.220	.377
	Positive	.327	.220	.377
	Negative	-.298	-.155	-.248
Kolmogorov-Smirnov Z		.926	.623	1.068
Asymp. Sig. (2-tailed)		.358	.832	.204

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition 15m/sec)

		10min	20min	30min
N		8	8	8
Normal Parameters[a,b]	Mean	.8750	1.1250	1.2500
	Std. Deviation	1.12599	.83452	1.28174
Most Extreme Differences	Absolute	.281	.228	.210
	Positive	.281	.185	.210
	Negative	-.219	-.228	-.165
Kolmogorov-Smirnov Z		.796	.644	.595
Asymp. Sig. (2-tailed)		.551	.801	.871

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition 30m/sec)

		10min	20min	30min
N		8	8	8
Normal Parameters[a,b]	Mean	.7500	1.1250	1.1250
	Std. Deviation	.70711	.83452	.83452
Most Extreme Differences	Absolute	.263	.228	.228
	Positive	.237	.185	.185
	Negative	-.263	-.228	-.228
Kolmogorov-Smirnov Z		.744	.644	.644
Asymp. Sig. (2-tailed)		.637	.801	.801

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition 60m/sec)

		10min	20min	30min
N		8	8	8
Normal Parameters[a,b]	Mean	1.6250	1.7500	1.8750
	Std. Deviation	.74402	.88641	.99103
Most Extreme Differences	Absolute	.300	.301	.311
	Positive	.300	.301	.311
	Negative	-.200	-.199	-.247
Kolmogorov-Smirnov Z		.847	.852	.881
Asymp. Sig. (2-tailed)		.469	.462	.420

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition 150m/sec)

		10min	20min	30min
N		8	8	8
Normal Parameters[a,b]	Mean	1.0000	.5000	.7500
	Std. Deviation	.92582	.53452	.70711
Most Extreme Differences	Absolute	.235	.325	.263
	Positive	.235	.325	.237
	Negative	-.235	-.325	-.263
Kolmogorov-Smirnov Z		.665	.920	.744
Asymp. Sig. (2-tailed)		.769	.366	.637

a. Test distribution is Normal.

b. Calculated from data.

D.3.3 Results on vection duration

One-Sample Kolmogorov-Smirnov Test

		3m/sec	8m/sec	15m/sec	30m/sec	60m/sec	150m/sec
N		8	8	8	8	7	8
Normal Parameters[a,b]	Mean	.0688	.2036	.2101	.5227	.4441	.1290
	Std. Deviation	.09308	.31927	.27592	.41191	.35809	.13890
Most Extreme Differences	Absolute	.283	.319	.264	.190	.200	.227
	Positive	.283	.319	.264	.148	.200	.227
	Negative	-.230	-.262	-.223	-.190	-.141	-.176
Kolmogorov-Smirnov Z		.800	.901	.748	.537	.529	.643
Asymp. Sig. (2-tailed)		.543	.391	.631	.935	.942	.803

a. Test distribution is Normal.

b. Calculated from data.

D.3.4 Results on SSQ scores

One-Sample Kolmogorov-Smirnov Test (Condition 3m/sec)

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	3.5775	14.2125	26.1000	15.4275
	Std. Deviation	4.93742	13.7025	27.27498	14.19758
Most Extreme Differences	Absolute	.391	.222	.206	.212
	Positive	.391	.222	.206	.212
	Negative	-.261	-.150	-.169	-.151
Kolmogorov-Smirnov Z		1.105	.629	.582	.600
Asymp. Sig. (2-tailed)		.174	.824	.887	.864

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition 8m/sec)

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	15.5025	27.4775	36.5400	29.4525
	Std. Deviation	15.24482	19.40476	37.1562	22.74404
Most Extreme Differences	Absolute	.220	.183	.229	.177
	Positive	.220	.172	.229	.177
	Negative	-.180	-.183	-.163	-.129
Kolmogorov-Smirnov Z		.623	.518	.647	.500
Asymp. Sig. (2-tailed)		.832	.951	.797	.964

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition 15m/sec)

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	21.4650	36.0050	38.2800	36.4650
	Std. Deviation	11.11376	22.8301	14.4086	15.8360
Most Extreme Differences	Absolute	.240	.152	.220	.202
	Positive	.233	.143	.155	.119
	Negative	-.240	-.152	-.220	-.202
Kolmogorov-Smirnov Z		.679	.429	.623	.573
Asymp. Sig. (2-tailed)		.745	.993	.832	.898

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition 30m/sec)

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	29.8125	29.3725	46.9800	38.8025
	Std. Deviation	21.8960	23.4289	32.3792	26.96489
Most Extreme Differences	Absolute	.188	.199	.314	.201
	Positive	.188	.199	.314	.201
	Negative	-.168	-.141	-.186	-.114
Kolmogorov-Smirnov Z		.532	.562	.888	.567
Asymp. Sig. (2-tailed)		.940	.910	.409	.904

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition 60m/sec)

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	28.6200	44.5325	57.4200	48.6200
	Std. Deviation	20.39738	28.1985	52.3159	34.39406
Most Extreme Differences	Absolute	.200	.256	.184	.207
	Positive	.200	.256	.184	.207
	Negative	-.180	-.138	-.136	-.122
Kolmogorov-Smirnov Z		.566	.725	.520	.585
Asymp. Sig. (2-tailed)		.906	.670	.950	.884

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition 150m/sec)

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	23.8500	36.9525	53.9400	42.0750
	Std. Deviation	17.66465	19.1921	28.27165	20.75134
Most Extreme Differences	Absolute	.291	.174	.208	.179
	Positive	.209	.146	.165	.153
	Negative	-.291	-.174	-.208	-.179
Kolmogorov-Smirnov Z		.823	.493	.589	.506
Asymp. Sig. (2-tailed)		.507	.968	.878	.960

a. Test distribution is Normal.

b. Calculated from data.

D.4 Normal distribution tests for data collected in Experiment 3

D.4.1 Results on nausea ratings

One-Sample Kolmogorov-Smirnov Test (Condition: 3m/sec)

		5 min	10 min	15 min	20 min	25 min	30 min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.1250	.3750	.5000	.5000	.8750	1.3750
	Std. Deviation	.35355	.51755	.75593	.53452	.99103	1.59799
Most Extreme Differences	Absolute	.513	.391	.371	.325	.311	.305
	Positive	.513	.391	.371	.325	.311	.305
	Negative	-.362	-.261	-.254	-.325	-.247	-.195
Kolmogorov-Smirnov Z		1.451	1.105	1.049	.920	.881	.863
Asymp. Sig. (2-tailed)		.050	.174	.221	.366	.420	.445

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: 8m/sec)

		5 min	10 min	15 min	20 min	25 min	30 min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.1250	1.2500	1.8750	2.6250	3.0000	3.2500
	Std. Deviation	.35355	1.58114	1.72689	1.68502	1.92725	1.75255
Most Extreme Differences	Absolute	.513	.438	.346	.270	.323	.307
	Positive	.513	.438	.346	.270	.323	.307
	Negative	-.362	-.215	-.306	-.167	-.190	-.238
Kolmogorov-Smirnov Z		1.451	1.238	.979	.763	.914	.868
Asymp. Sig. (2-tailed)		.050	.093	.293	.606	.374	.439

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: 15m/sec)

		5 min	10 min	15 min	20 min	25 min	30 min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	1.0000	2.3750	3.0000	3.7500	4.1250	4.5000
	Std. Deviation	1.41421	2.38672	2.32993	2.31455	2.35660	2.26779
Most Extreme Differences	Absolute	.260	.312	.151	.210	.270	.337
	Positive	.260	.312	.151	.165	.213	.254
	Negative	-.240	-.186	-.151	-.210	-.270	-.337
Kolmogorov-Smirnov Z		.736	.884	.427	.593	.763	.954
Asymp. Sig. (2-tailed)		.651	.416	.993	.874	.605	.323

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 30m/sec)**

		5 min	10 min	15 min	20 min	25 min	30 min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.2500	1.3750	2.0000	2.6250	3.0000	3.5000
	Std. Deviation	.46291	1.92261	1.85164	1.84681	1.92725	1.85164
Most Extreme Differences	Absolute	.455	.452	.250	.170	.198	.231
	Positive	.455	.452	.250	.170	.177	.144
	Negative	-.295	-.237	-.170	-.118	-.198	-.231
Kolmogorov-Smirnov Z		1.288	1.279	.707	.480	.560	.655
Asymp. Sig. (2-tailed)		.072	.076	.699	.976	.912	.785

a. Test distribution is Normal.

b. Calculated from data.

D.4.2 Results on vection ratings

One-Sample Kolmogorov-Smirnov Test **(Condition: 3m/sec)**

		10 min	20 min	30 min
N		8	8	8
Normal Parameters[a,b]	Mean	1.0000	1.2500	1.3750
	Std. Deviation	.92582	1.03510	1.18773
Most Extreme Differences	Absolute	.375	.220	.249
	Positive	.375	.220	.249
	Negative	-.250	-.155	-.164
Kolmogorov-Smirnov Z		1.061	.623	.704
Asymp. Sig. (2-tailed)		.211	.832	.705

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 8m/sec)**

		.10 min	20 min	30 min
N		8	8	8
Normal Parameters[a,b]	Mean	1.2500	1.1250	1.1250
	Std. Deviation	1.16496	.99103	.99103
Most Extreme Differences	Absolute	.335	.300	.300
	Positive	.335	.300	.300
	Negative	-.183	-.200	-.200
Kolmogorov-Smirnov Z		.947	.849	.849
Asymp. Sig. (2-tailed)		.331	.467	.467

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 15m/sec)**

		10 min	20 min	30 min
N		8	8	8
Normal Parameters[a,b]	Mean	1.7500	2.1250	2.1250
	Std. Deviation	1.16496	.99103	.99103
Most Extreme Differences	Absolute	.240	.311	.311
	Positive	.240	.247	.247
	Negative	-.233	-.311	-.311
Kolmogorov-Smirnov Z		.679	.881	.881
Asymp. Sig. (2-tailed)		.745	.420	.420

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 30m/sec)**

		10 min	20 min	30 min
N		8	7	7
Normal Parameters[a,b]	Mean	.8750	1.0000	1.2857
	Std. Deviation	.64087	.81650	1.25357
Most Extreme Differences	Absolute	.327	.214	.304
	Positive	.298	.214	.304
	Negative	-.327	-.214	-.200
Kolmogorov-Smirnov Z		.926	.567	.805
Asymp. Sig. (2-tailed)		.358	.905	.535

a. Test distribution is Normal.

b. Calculated from data.

D.4.3 Resulst on vection duration

One-Sample Kolmogorov-Smirnov Test

		3m/sec	8m/sec	15m/sec	30m/sec
N		8	8	8	8
Normal Parameters[a,b]	Mean	.5439	.4764	.5937	.5069
	Std. Deviation	.38895	.44643	.34348	.47262
Most Extreme Differences	Absolute	.167	.262	.145	.257
	Positive	.167	.240	.118	.220
	Negative	-.152	-.262	-.145	-.257
Kolmogorov-Smirnov Z		.473	.740	.411	.727
Asymp. Sig. (2-tailed)		.979	.645	.996	.666

a. Test distribution is Normal.

b. Calculated from data.

D.4.4 Results on SSQ scores

One-Sample Kolmogorov-Smirnov Test (Condition: 3m/sec)

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	17.8875	20.8450	26.1000	24.3100
	Std. Deviation	16.47451	19.74545	22.85776	19.27876
Most Extreme Differences	Absolute	.194	.249	.203	.311
	Positive	.194	.249	.203	.311
	Negative	-.139	-.146	-.152	-.191
Kolmogorov-Smirnov Z		.548	.705	.574	.880
Asymp. Sig. (2-tailed)		.925	.703	.897	.421

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: 8m/sec)

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	39.3525	35.0575	55.6800	47.6850
	Std. Deviation	29.92472	20.23306	47.05819	27.75459
Most Extreme Differences	Absolute	.266	.343	.241	.270
	Positive	.266	.343	.241	.270
	Negative	-.190	-.271	-.187	-.182
Kolmogorov-Smirnov Z		.752	.969	.683	.762
Asymp. Sig. (2-tailed)		.624	.305	.740	.606

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: 15m/sec)

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	62.0100	40.7425	55.6800	59.3725
	Std. Deviation	34.20744	15.12612	32.43262	28.01882
Most Extreme Differences	Absolute	.287	.200	.180	.185
	Positive	.118	.200	.125	.112
	Negative	-.287	-.175	-.180	-.185
Kolmogorov-Smirnov Z		.812	.564	.508	.522
Asymp. Sig. (2-tailed)		.524	.908	.958	.948

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 30m/sec)**

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	41.7375	42.6375	41.7600	48.6200
	Std. Deviation	22.19094	13.39967	21.04506	14.69043
Most Extreme Differences	Absolute	.133	.166	.250	.154
	Positive	.117	.166	.250	.154
	Negative	-.133	-.160	-.129	-.152
Kolmogorov-Smirnov Z		.375	.470	.707	.436
Asymp. Sig. (2-tailed)		.999	.980	.699	.991

a. Test distribution is Normal.

b. Calculated from data.

D.5 Normal distribution tests for data collected in Experiment 4

D.5.1 Results on nausea ratings

One-Sample Kolmogorov-Smirnov Test **(Condition: 7.6 deg/sec)**

		5 min	10 min	15 min	20 min	25 min	30 min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.1250	.1250	.2500	.5000	.8750	1.2500
	Std. Deviation	.35355	.35355	.70711	.75593	1.12599	1.58114
Most Extreme Differences	Absolute	.513	.513	.513	.371	.281	.285
	Positive	.513	.513	.513	.371	.281	.285
	Negative	-.362	-.362	-.362	-.254	-.219	-.215
Kolmogorov-Smirnov Z		1.451	1.451	1.451	1.049	.796	.807
Asymp. Sig. (2-tailed)		.050	.050	.050	.221	.551	.532

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: 20.4 deg/sec)

		5 min	10 min	15 min	20 min	25 min	30 min
N		8	8	8	8	8	8
Normal Parameters [a,b]	Mean	.6250	1.1250	1.8750	2.5000	3.2500	3.2500
	Std. Deviation	1.40789	2.03101	2.10017	2.26779	2.37547	2.37547
Most Extreme Differences	Absolute	.421	.400	.287	.212	.249	.249
	Positive	.421	.400	.287	.212	.164	.164
	Negative	-.329	-.290	-.186	-.135	-.249	-.249
Kolmogorov-Smirnov Z		1.192	1.130	.810	.600	.704	.704
Asymp. Sig. (2-tailed)		.117	.155	.527	.864	.705	.705

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test (Condition: 38.2 deg/sec)

		5 min	10 min	15 min	20 min	25 min	30 min
N		8	8	8	8	8	8
Normal Parameters [a,b]	Mean	1.0000	1.6250	3.1250	3.6250	4.5000	4.5000
	Std. Deviation	2.07020	2.06588	2.69590	2.32609	1.92725	1.92725
Most Extreme Differences	Absolute	.375	.244	.232	.221	.282	.282
	Positive	.375	.244	.162	.154	.218	.218
	Negative	-.315	-.216	-.232	-.221	-.282	-.282
Kolmogorov-Smirnov Z		1.061	.690	.656	.626	.797	.797
Asymp. Sig. (2-tailed)		.211	.728	.783	.828	.549	.549

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 76.4 deg/sec)**

		5 min	10 min	15 min	20 min	25 min	30 min
N		8	8	8	8	8	8
Normal Parameters[a,b]	Mean	.7500	1.3750	2.3750	2.7500	2.6250	3.0000
	Std. Deviation	1.16496	1.68502	2.32609	2.25198	2.26385	2.13809
Most Extreme Differences	Absolute	.365	.230	.221	.206	.234	.200
	Positive	.365	.230	.221	.206	.234	.200
	Negative	-.260	-.207	-.154	-.176	-.182	-.175
Kolmogorov-Smirnov Z		1.033	.652	.626	.582	.661	.566
Asymp. Sig. (2-tailed)		.236	.790	.828	.887	.775	.906

a. Test distribution is Normal.

b. Calculated from data.

D.5.2 Results on vection ratings

One-Sample Kolmogorov-Smirnov Test **(Condition: 7.6 deg/sec)**

		10 min	20 min	30 min
N		8	8	8
Normal Parameters[a,b]	Mean	.7500	.3750	.5000
	Std. Deviation	.70711	.51755	.53452
Most Extreme Differences	Absolute	.263	.391	.325
	Positive	.237	.391	.325
	Negative	-.263	-.261	-.325
Kolmogorov-Smirnov Z		.744	1.105	.920
Asymp. Sig. (2-tailed)		.637	.174	.366

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 20.4 deg/sec)**

		10 min	20 min	30 min
N		8	8	8
Normal Parameters[a,b]	Mean	1.1250	1.6250	1.6250
	Std. Deviation	.99103	.91613	.91613
Most Extreme Differences	Absolute	.300	.284	.284
	Positive	.300	.216	.216
	Negative	-.200	-.284	-.284
Kolmogorov-Smirnov Z		.849	.803	.803
Asymp. Sig. (2-tailed)		.467	.540	.540

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 38.2 deg/sec)**

		10 min	20 min	30 min
N		8	8	8
Normal Parameters[a,b]	Mean	1.7500	1.8750	1.8750
	Std. Deviation	.70711	.64087	.64087
Most Extreme Differences	Absolute	.263	.327	.327
	Positive	.237	.298	.298
	Negative	-.263	-.327	-.327
Kolmogorov-Smirnov Z		.744	.926	.926
Asymp. Sig. (2-tailed)		.637	.358	.358

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 76.4deg/sec)**

		10 min	20 min	30 min
N		8	8	8
Normal Parameters[a,b]	Mean	1.5000	2.0000	2.0000
	Std. Deviation	1.06904	1.06904	.75593
Most Extreme Differences	Absolute	.305	.250	.250
	Positive	.195	.175	.250
	Negative	-.305	-.250	-.250
Kolmogorov-Smirnov Z		.863	.707	.707
Asymp. Sig. (2-tailed)		.446	.699	.699

a. Test distribution is Normal.

b. Calculated from data.

D.5.3 Results on vection duration

One-Sample Kolmogorov-Smirnov Test

		7.6deg	20.4deg	38.2deg	76.4deg
N		8	8	8	8
Normal Parameters[a,b]	Mean	.1646	.4411	.5308	.5843
	Std. Deviation	.28988	.39364	.29365	.41428
Most Extreme Differences	Absolute	.315	.232	.134	.213
	Positive	.315	.185	.117	.161
	Negative	-.285	-.232	-.134	-.213
Kolmogorov-Smirnov Z		.890	.657	.379	.603
Asymp. Sig. (2-tailed)		.407	.781	.999	.860

a. Test distribution is Normal.

b. Calculated from data.

D.5.4 Results on SSQ scores

One-Sample Kolmogorov-Smirnov Test **(Condition: 7.6 deg/sec)**

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	15.5025	24.6350	26.1000	25.2450
	Std. Deviation	8.73984	15.56077	22.85776	14.65638
Most Extreme Differences	Absolute	.284	.232	.220	.116
	Positive	.216	.232	.220	.100
	Negative	-.284	-.146	-.155	-.116
Kolmogorov-Smirnov Z		.803	.657	.621	.329
Asymp. Sig. (2-tailed)		.540	.780	.835	1.000

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 20.4 deg/sec)**

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	40.5450	39.7950	59.1600	51.4250
	Std. Deviation	38.07473	27.10390	58.94026	43.09702
Most Extreme Differences	Absolute	.175	.262	.241	.219
	Positive	.175	.262	.241	.219
	Negative	-.143	-.158	-.158	-.171
Kolmogorov-Smirnov Z		.496	.740	.682	.620
Asymp. Sig. (2-tailed)		.966	.644	.741	.836

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 38.2 deg/sec)**

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	60.8175	42.6375	67.8600	63.1125
	Std. Deviation	35.30629	32.64999	36.78185	33.71561
Most Extreme Differences	Absolute	.261	.308	.165	.152
	Positive	.131	.308	.136	.152
	Negative	-.261	-.200	-.165	-.136
Kolmogorov-Smirnov Z		.738	.870	.466	.430
Asymp. Sig. (2-tailed)		.647	.435	.982	.993

a. Test distribution is Normal.

b. Calculated from data.

One-Sample Kolmogorov-Smirnov Test **(Condition: 76.4 deg/sec)**

		NS	OS	DS	TS
N		8	8	8	8
Normal Parameters[a,b]	Mean	46.5075	47.3750	67.8600	59.8400
	Std. Deviation	42.18533	33.59476	60.64735	47.97874
Most Extreme Differences	Absolute	.275	.221	.364	.344
	Positive	.275	.221	.364	.344
	Negative	-.190	-.169	-.187	-.218
Kolmogorov-Smirnov Z		.777	.626	1.028	.973
Asymp. Sig. (2-tailed)		.583	.827	.241	.300

a. Test distribution is Normal.

b. Calculated from data.

Appendix E Experimental instructions for subjects

E.1 Experimental instructions for subjects in Experiment 1a & 1b

1) Please give full concentration and do your best in this experiment.
2) Please keep your eyes open during the whole experiment (of cause, you can blink, but do not close your eyes).
3) Please follow the instructions that the experimenter gives you during the experiment.
4) At the beginning of the experiment, please put your hands on your knees (underneath the desk), sit still and wait for the verbal instruction: "You are now entering the experimental environment"
5) Please look straight ahead unless you are instructed to turn.
6) Every 5 minutes, you will be asked to give the nausea rating and vection rating as following:

Nausea Rating Scale

0: no symptom

1: slight unpleasant symptom

2: mild unpleasant symptom

3: mild nausea

4: mild to moderate nausea

5: moderate nausea but can continue

6: moderate nausea, and want to stop

Vection Rating Scale

0: none

1: slight

2: moderate

3: strong

E.2 Experimental instructions for subjects in Experiment 2, 3, & 4

1) Please give full concentration and do your best in this experiment.

2) Please keep your eyes open during the whole experiment (of cause, you can blink, but do not close your eyes).

3) Please follow the instructions that the experimenter gives you during the experiment.

4) At the beginning of the experiment, please put your hands on your knees (underneath the desk), sit still and wait for the verbal instruction: "You are now entering the experimental environment".

5) Please really imagine you are immersed in the virtual environment.

6) Please look straight ahead. If you find object (for example, cross, circle and cube etc, please refer to the diagram the experimenter show to you) suddenly pops up in front of you in the environment, please speak out and describe what you see to the experimenter.

7) When you have the feeling of vection, please press the response button and don't release until you loss the sensation of vection.

8) The whole duration is 30 minutes. Every five minutes, you will be asked to give the nausea rating and every ten minutes, you will be asked to give the vection rating(please refer to the sheets on describing nausea rating and vection rating).

   Nausea Rating Scale

   0: no symptom

   1: slight unpleasant symptom

   2: mild unpleasant symptom

   3: mild nausea

4: mild to moderate nausea

5: moderate nausea but can continue

6: moderate nausea, and want to stop

Vection Rating Scale

0: none

1: slight

2: moderate

3: strong

Appendix F Motion Sickness Susceptibility Survey

暈浪敏感調查

This survey is being conducted to examine the motion sickness susceptibility of the Hong Kong Chinese population. All information in this survey will be kept confidential. This survey is not a requirement of this course and participation is to be done on a voluntary basis.
這是一個有關中國人對暈浪的敏感性調查， 所有調查所得的資料將會被保密。

Instructions: Please fill in this survey. Circle the answer which most closely corresponds to your own experience. Feel free to add any comments you would like to make at the end of the survey.
請圈出你的答案。

Age 年齡：_____

Sex 性別：M F

School 學院：Business Engineering Humanities Science

The term motion sickness is a refers to symptoms, such as dizziness, fatigue, nausea, headache, sweating, and vomiting, which can be evoked in susceptible individuals by the perception of various kinds of periodic motion,

暈浪的定義就是一种病徵， 例流汗，作嘔，頭暈，頭痛或嘔吐。

1。 In the pass 12 months how often have you experienced motion sickness while travelling as a passenger in the following situations? (E.g. If you travel by bus 300 times a year and experience motion sickness 30 times, that would be 10% of the time)

Car/Taxi 私家車/的士	0%	1%-10%	11%-40%	41%-74%	75%-100%
Buses 巴士	0%	1%-10%	11%-40%	41%-74%	75%-100%
Cross-Ferry 渡輪	0%	1%-10%	11%-40%	41%-74%	75%-100%
Jet-Foil 飛翔船	0%	1%-10%	11%-40%	41%-74%	75%-100%
Trains (MTR/KCR) 火車	0%	1%-10%	11%-40%	41%-74%	75%-100%

Elevators 升降机	0%	1%-10%	11%-40%	41%-74%	75%-100%

2. Please circle the symptoms experienced while in the following situations:
請圈出在暈浪的病徵 ：

Car/Taxi 私家車/的士	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Buses 巴士	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Cross-Ferry 渡輪	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Jet-Foil 飛翔船	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Trains (MTR/KCR) 火車	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Elevators 升降机	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐

3. In general, how susceptible to motion sickness are you?
通常，你對暈浪的敏感程度有几大？

Not at all 從不	Slightly 很少	Moderately 一般	Very 非常	Extremely 极端

Comments:
其他意見：

Thank you for participating in this survey. If you have any comments or questions please contact:

4. How many hours do you spend on computer in a week?
   0-5 6-1011-15 16-20 21-25 over 25
5. Did you use virtual reality in the past week? Yes/No

Appendix G Simulator Sickness Questionnaire

SYMPTOM CHECKLIST (Pre-exposure)

confidential

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

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

胃口增加	22. Increased appetite	No	Yes (Slight Moderate Severe)
想去洗手間	23. Desire to move bowels	No	Yes (Slight Moderate Severe)
迷惘	24. Confusion	No	Yes (Slight Moderate Severe)
打嗝	25. Burping	No	Yes (Slight Moderate Severe)
嘔吐	26. Vomiting	No	Yes (Slight Moderate Severe)
其他	27. Other	No	Yes (Slight Moderate Severe)

Appendix H Simulator Sickness Questionnaire

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 I Terminology used in experiment 1 to 4

- *Nausea:* a stomach distress with distaste for food and an urge to vomit. [Merriam-Webster's collegiate dictionary. 2000, 10th edition. Springfield, Mass.: Merriam-Webster. ISBN: 0877797099]

  Nausea: 作嘔，惡心；胃部的一種不適應感，感到沒有胃口並且想嘔吐。

- *Dizziness:* having a whirling sensation in the head with a tendency to fall. [Merriam-Webster's collegiate dictionary. 2000, 10th edition. Springfield, Mass.: Merriam-Webster. ISBN: 0877797099]

  NB: This sensation can occur when viewing visual surround that is moving too fast for the eye to catch.

  Dizziness: 眩暈的，眼花的，並且感到不平衡。

- *Eyestrain:* weariness or a strained state of the eye. [Merriam-Webster's collegiate dictionary. 2000, 10th edition. Springfield, Mass.: Merriam-Webster. ISBN: 0877797099]

  Eyestrain: 眼睛疲勞，疲乏或緊張。

- *Vection:* visually induced perception of self-motion; this sensation of self-motion is opposite in direction to the actual motion of the visual stimulus. [Handbook of sensory physiology, Vol VIII. 1978. SpringVerlag.]

  NB: this sensation is a REAL feeling of self-motion even though you are physically stationary. Just seeing something that is moving visually in front of you does NOT automatically mean you will have vection sensation. You must have the feeling that you are moving.

  Vection: 通常是由視覺引起的一種自己在移動的錯覺。由于觀察者看到一些物體或者景象在移動，他錯誤地以為自己在沿着那些物體或者景象移動的反方嚮移動。即使從物理上來說，妳的身體是靜止的，但是妳有一種自己在移動的真實感覺。僅僅看到一些物體在妳面前移動並非意味着妳一定會有這種自己在移動的錯覺，你必须要有一种自己在移动的感觉。

  A real world example of this phenomenon occurs when a passenger in a stationary train feels that they have started moving when in fact it is a train on an adjacent track that has begun to move.

在生活中，也可以找到 Vection 的例子。比如当一位旅客坐在静止的火车内，当相邻的火车开始慢慢移动的时候，这位旅客会有一种错觉，以为是自己坐的火车在移动。

Question: Now, please explain to the experimenter what is "vection".

If you have any question now about nausea, dizziness, eyestrain and vection, please ask the experimenter.