Cybersickness with virtual reality systems: experimental studies and development of a measuring metric to quantify visual scene movement in a virtual reality simulation

By

Lo Wun Tak, B.Sc

A Thesis Presented to

The Hong Kong University of Science and Technology

in Partial Fulfillment

of the Requirements for

the Degree of Master of Philosophy

in

Industrial Engineering and Engineering Management

Hong Kong December 1998

Authorization

I hereby declare that I am the sole author of the thesis.

I authorize the Hong Kong University of Science and Technology to lend this thesis to order institutions or individuals for the purpose of scholarly research.

I further authorize the Hong Kong University of Science and Technology to reproduce the thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Cybersickness with virtual reality systems: experimental studies and development of a measuring metric to quantify visual scene movement in a virtual reality simulation

By

Lo Wun Tak, B.Sc

APPROVED:

DR. RICHARD H. Y. SO — SUPERVISOR
DEPARTMENT OF INDUSTRIAL ENGINEERING AND ENGINEERING MANAGEMENT

PROFESSOR MITCHELL M. TSENG — HEAD OF DEPARTMENT
DEPARTMENT OF INDUSTRIAL ENGINEERING AND ENGINEERING MANAGEMENT

DR. VINCENT G. DUFFY — CHAIRMAN
DEPARTMENT OF INDUSTRIAL ENGINEERING AND ENGINEERING MANAGEMENT

PROFESSOR MARTIN HELANDER — COMMITTEE MEMBER
DEPARTMENT OF INDUSTRIAL ENGINEERING AND ENGINEERING MANAGEMENT

Acknowledgements

I would like to express my grateful appreciation to my supervisor Dr. Richard H. Y. So for his support, guidance and advice during the research.

My deep appreciation goes Professor Martin Helander, Dr. Vincent G. Duffy, Dr. Ravindra S. Goonetilleke, Dr. Heloisa H. O. M. Shih and Dr Halimahtun Khalid for giving me a lot of advice during my presentation in human factor seminars. Further, I would like to thank Dr. Fugee Tsung for his discussion with design of experiment.

Sincere gratefulness to Shyam, Edmond, and Peter for their discussion and help. I would like to thank Denil and German for helping me to solve some technical problems that I came across when developing the virtual environment and computer programs. Additional thanks are extended to communication tutor Vera Breuer, other faculty members, staff and my UST friends Kan and Ivan.

Finally, I would like to take this opportunity to thank my parents, my three brothers Peter, Patrick and Joseph for their encouragement and support throughout my study.

Abstract

Visual scene movement in a virtual reality simulation can cause symptoms of motion sickness (cybersickness). The purposes of this research were to develop a measuring metric to quantify the visual scene movement in a virtual reality simulation and to verify that the proposed measures do significantly influence the levels of cybersickness.

A review of literature indicates that cybersickness is a form of vection-induced motion sickness. The term 'vection' is used to describe the self-motion illusion generated by visual scene movement. This self-motion illusion is in opposite direction to the scene movement and can be nauseogenic. A preliminary experiment has been conducted to investigate the effects of scene oscillations on the rated level of cybersickness. The results showed that the presence of scene movement could significantly increase levels of cybersickness. This experiment confirmed that visual stimulus is an important factor that would influence the rated level of cybersickness. Further reviews of literature indicates that there is yet no quantitative unit to measure visual stimuli in a virtual environment (a computer generated 3D environment). Based on previous studies with vection-induced motion sickness using rotating drums, a new unit called 'Spatial Velocity (SV)' is proposed to quantify visual stimuli. The proposed 'spatial velocity' metric is a measure of the rate of movement of contrasted information perceived by a subject during a virtual reality simulation. Movements of spatially contrasted pattern (e.g. black and white strip) have previously been shown to induce sense of self-motion illusion

(vection) and symptoms of motion sickness. This forms the theoretical basis for the 'spatial velocity' metric.

The 'spatial velocity' has two components: (i) 'spatial frequency', and (ii) 'scene velocity'. 'Spatial frequency' is used to quantify scene complexity and 'scene velocity' is used to quantify speed and direction of visual scene movement. Both 'spatial frequency' and 'scene velocity' can be measured, therefore, 'spatial velocity' can be a metric to quantify the movements of visual scene of different complexity. This metric is the first of its kind in the field of cybersickness research. The algorithms and procedures to measure 'spatial velocity' are presented in the thesis.

Two experiments have been conducted to study the effect of scene velocity and scene complexity on the rated level of cybersickness. The results of these experiments suggested that increase in either scene velocity or spatial frequency would significantly increase the rated level of cybersickness. Besides, the sickness ratings increase linearly with 'spatial velocity' in the fore-and-aft and yaw axes. This verifies that 'spatial velocity' is an appropriate measuring metric to quantify visual stimuli in a virtual environment.

The application of the 'spatial velocity' metric to the formulation of a Cybersickness Dose Value (CSDV) is also discussed in the thesis. This CSDV is proposed to be a time integral of a frequency weighted time history of 'spatial velocity' over the total duration of simulation exposure.

Recommendations on future work towards the establishment of a Cybersickness Dose Value are included.

Table of content

List of Figures

List of Tables

Chapter 1 Introduction

1.1 General introduction to Virtual Reality (VR) systems

Virtual reality is a well-known technology. It allows a user to interact with a computer generated (virtual) environment. A common way to present this virtual environment is through a head-mounted display (HMD). Users can select their views by moving their heads (i.e. a head-coupled virtual reality system). A head position sensor is used to measure the user's head position and orientation so that a host computer can update images of the virtual environment according to the user's viewpoint. In addition, a 3D mouse can be used to navigate through the virtual environment and a Cyberglove™ to interact with computer-generated virtual objects.

1.2 Use of virtual reality systems

Virtual reality systems have been used in a wide range of applications such as simulation training (e.g. virtual CNC Milling Machine: Lin *et al.*, 1996; driving simulator: Bayarri *et al.*, 1996; teleoperation: Kim *et al.*, 1992; medical training and education: Satava and Jones, 1997; firefighters training: Bliss *et al.*, 1997). For example, doctors can practice a complicated operation in a virtual environment several times, so that the chance of success in real operation will increase. Military training always involves the use of virtual reality systems. Pilots can practice flying in different situations (e.g. flying at night, or in bad climate, even in a battlefield).

Virtual reality simulator can be an effective way to train workers to operate machines. Since there is no need to take the machine off-line for training purposes, as a result, money and time can be saved. A virtual reality environment can simulate a space, real size models of human skeleton, or even an event happened in the past, further it can be used as teaching material in class. On the other hand, virtual reality systems are largely used in entertainment. Many virtual simulation games exist (e.g. virtual flight, fight, driving etc.).

1.3 Problems associated with the use of virtual reality systems

Although virtual reality systems seem to be powerful, the uses of VR systems have some side effects. Users can suffer from simulator sickness. Clare Regan (1995) studied the effects of a head-coupled virtual reality system. In her study, 61% of the total 150 subjects reported symptoms of malaise. She stated that after the use of a virtual reality system for 20 minutes, the most common symptoms were dizziness, headaches, eyestrain, stomach awareness and severe nausea. Five percent of the subjects withdrew from the experiment due to severe nausea or severe dizziness. In 1994, So studied the effect of lags on motion sickness with a head-coupled virtual reality system. He reported that about 60% (29 out of 48) subjects suffered 'general discomfort' after 20 minutes flight simulation. Four subjects had to withdraw from the study after reporting moderate nausea. Nowadays, the term 'cybersickness' is used to describe the phenomenon of simulator sickness with virtual reality systems (McCauley and Sharkey, 1992).

1.4 Purposes of the research

This study aims to develop a metric to quantify visual scene movement in a virtual reality simulation and to determine the cause of cybersickness during the use of head-coupled virtual reality systems. The specific objectives are to: (i): determine the effects of visual scene movement on the rated level of cybersickness; (ii) propose and develop a quantifying metric for measuring visual scene movement during a virtual reality simulation; (iii): study the effects of visual scene velocity (a major component of the proposed metric) of a virtual reality simulation and (iv); determine the effects of visual scene complexity (a major component of the proposed metric) on the level of cybersickness.

1.5 Organization of the thesis

The beginning of the thesis is the introduction to motion sickness and the review of literature (Chapters one to three). The second part documents the development of the 'Spatial Velocity' metric to quantify visual scene movement in a virtual reality simulation (Chapters four to six). The third part presents the experimental work performed to verify the 'spatial velocity' metric (Chapters seven to nine). Finally the last part is the general discussion and conclusion (Chapter ten). The structure of the thesis is illustrated in Figure 1.1

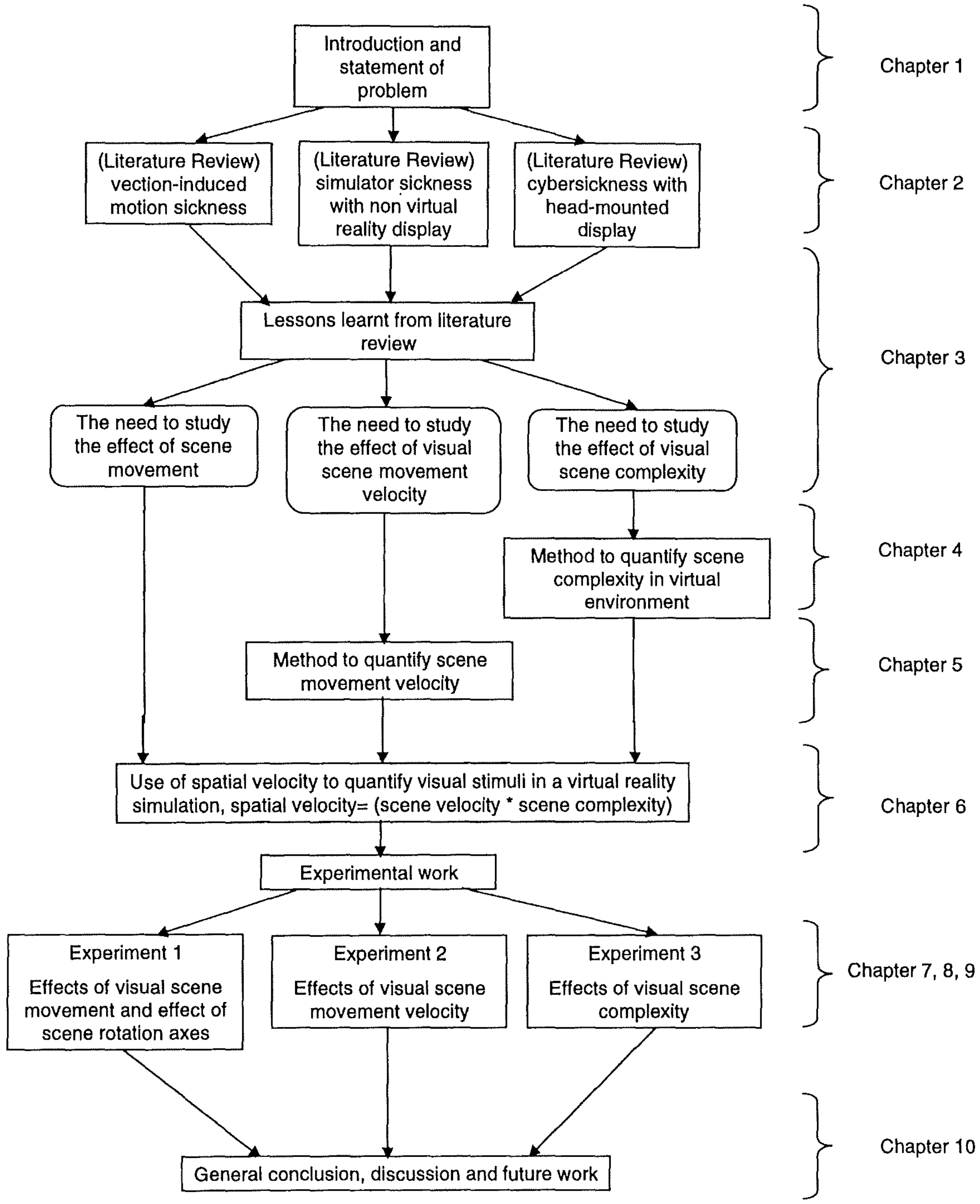


Figure 1.1 Outline of the thesis

Chapter 2 Review of literature

2.1 Introduction to vection-induced motion sickness, simulator sickness and cybersickness

Motion sickness is a general term to describe symptoms occurring in different types of transport (land, sea and air: cars, buses, trains, ships, hydrofoils, planes and spacecraft etc.), activities and devices (simulators). For example, people exposed to the motion of ship may experience motion sickness. Lawther and Griffin (1988) suggested that vomiting and illness ratings of seasickness were found to be linearly related to the vertical motion of the ship. Exposure in fairground simulator apparatus can cause vomiting. Besides, by viewing some films (especially for those simulating navigation) could produce the similar effect of motion sickness. The common symptoms of motion sickness include nausea, dizziness, headache, sweating, vomiting and vertigo.

Motion sickness can be produced by different stimuli. Conditions involving body motion can cause motion sickness. Conditions only involving movement of a visual scene without body motion can also produce similar symptoms of motion sickness. Human use visual and vestibular systems to detect motion. Nowadays, some theories of motion sickness are based on the conflict between the information received from visual and vestibular systems. In 1975, Reason and

Brand used two types of categories to define the sensory conflict. Type I: visual and vestibular systems simultaneously signal differently, Type IIa: visual system signals in the absence of an expected vestibular signal, and Type IIb: vestibular system signals in the absence of an expected visual signal. Type IIa motion sickness is a type of visually-induced sickness. The use of sensory conflict theory (Reason and Brand, 1975) and sensory rearrangement theory (Reason, 1978) to explain simulator sickness and cybersickness is widely adopted in many published studies. Table 2.1 illustrates the type of motion cue mismatch produced by various provocative stimuli. Figure 2.1 illustrates a simplified conceptual model of the generation of motion sickness due to sensory conflict.

Table 2.1 Type of motion cue mismatch produced by various provocative stimuli (adapted from Griffin, 1990)

	Category of motion cue mismatch	
	Visual (A) / vestibular (B)	Canal (A) / otolith (B)
Type I A and B simultaneously give contradictory or uncorrelated information	• Watching waves from a ship • Use of binoculars in a moving vehicle • Making head movements when vision is distorted by an optical device • 'Pseudo-Coriolis' stimulation	• Making head movements whilst rotating (Coriolis or cross-coupled stimulation) • Making head movements in an abnormal environment which may be constant (e.g. hyper- or hypo-gravity) or fluctuating (e.g. linear oscillation) • Space sickness • Vestibular disorders (e.g. Ménière's disease, acute labyrinthitis, trauma labyrinthectomy)
Type IIa A signals in absence of expected B signals	• Cinerama sickness • Simulator sickness • 'Haunted Swing' • Circularvection	• Positional alcohol nystagmus • Caloric stimulation of semi-circular canals • Vestibular disorders (e.g. pressure vertigo, cupulolith-iasis)
Type IIb B signals in absence of expected A signals	• Looking inside a moving vehicle without external visual reference (e.g. below deck in boat) • Reading in a moving vehicle	• Low-frequency (<0.5 Hz) translational oscillation • Rotating linear acceleration vector (e.g. 'barbecue-spit' rotation, rotation about an off-vertical axis)

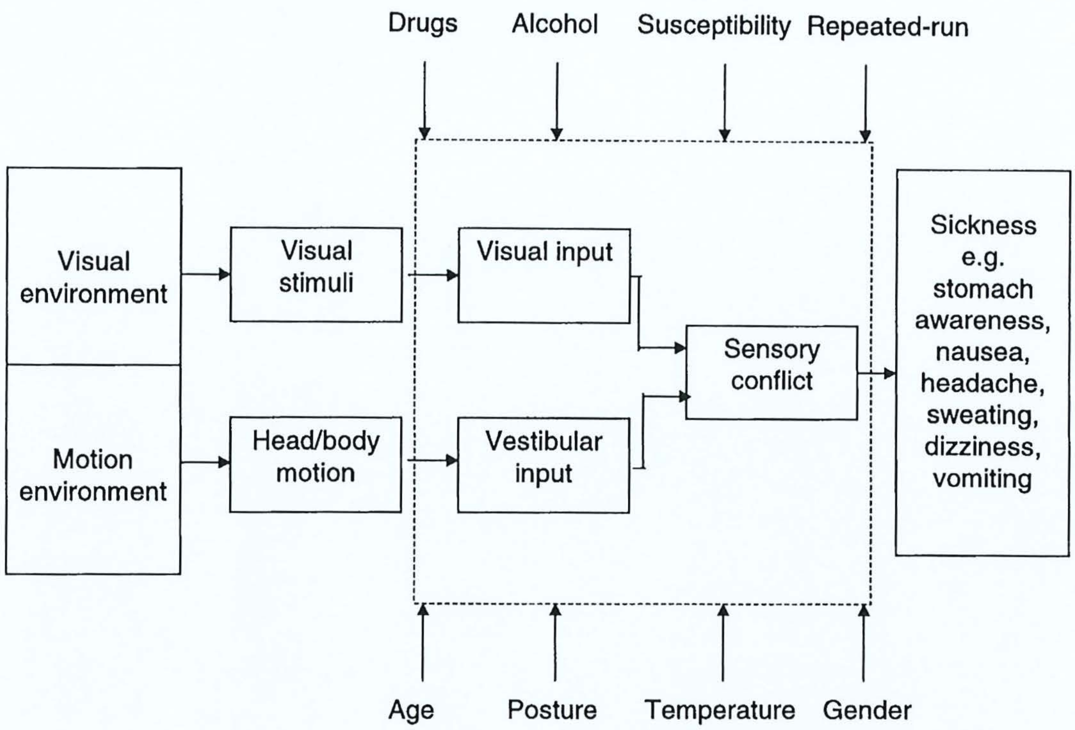


Figure 2.1 A simplified conceptual model of the generation of motion sickness due to sensory conflict. Factors affecting the sickness are also illustrated (modified from Griffin, 1990)

Factors shown in Figure 2.1 have been controlled or measured in the experiments of this study. Their influences on the findings of these results are discussed in Chapter 10.

As illustrated in Figure 2.1, the sensory conflict theory states that in situations where signals perceived by visual and vestibular systems are in conflict with each other, sickness symptoms will occur.

For example, the use of binoculars in a moving vehicle can generate Type I motion sickness (Table 2.1). In this case, the visual environment (according to the movements of the head while using the binoculars) is not fully compatible with the motion environment. As illustrated in Figure 2.1, the vestibular input signals (according to the motion of the moving vehicle) and the visual input signals are in conflict, therefore, sickness occurs.

Simulator sickness and cybersickness are Type IIa motion sickness (Table 2.1). In most simulator or virtual reality systems, the movements of the visual scene are pre-determined by computer programs or controlled using hand-held navigation tools (e.g. 3D mouse), While the scene is moving, the users themselves are physically stationary. In these situations, the visual input suggests body movements but the vestibular input detects that there is no actual body or head movements, therefore, the visual-vestibular conflict arises (see Figure 2.1).

Reading in a moving vehicle can generate Type IIb motion sickness (Table 2.1). The vestibular system perceives the motion of the body, but the visual system detects there is no relative movement between the reading material and the person. The visual-vestibular conflict arises and the experience can be nauseogenic.

In this thesis, attention will be focused on the occurrence of cybersickness, which is a type of vection-induced motion sickness. The key term 'vection' is used to describe self-motion illusion generated by visual scene moment. Vection is an illusion of self-motion that a stationary observer perceives from viewing a large field-of-view moving scene. This self-motion illusion goes in the opposite direction to that of the scene movement and such experience can be nauseogenic (Griffin, 1990). The resulting sickness is commonly known as vection-induced motion sickness. The sensory conflict theory states that the cause of motion sickness by vection is due to the absence of expected signals from the vestibular receptors (Reason and Brand, 1975). There are two kinds of vection: circular vection and linear vection.

In 1978, Dichgans and Brandt introduced the term circular vection. When stationary subjects are exposed to images rotating around themselves, they will feel that they are rotating even though they are stationary. Similarly, with linear vection, when stationary subjects look at a large field-of-view scene moving in a translational axis, they will perceive the illusion of self-motion in the opposite translational direction. One common example of linear vection is when a passenger of a stationary train looks at a nearby train which is slowly moving out of a station, the passenger will feel as if his/her own trains is moving slowly backward.

The visual scene movement of a simulator can provoke simulator sickness (Hettinger *et al.*, 1990). In a virtual reality system, operators are often exposed to moving scenes while they are physically stationary, this could cause vection-induced sickness. Cybersickness associated with VR systems are, therefore, a sub-set of vection-induced motion sickness.

2.2 Previous studies on vection-induced sickness using non-virtual reality display

2.2.1 Effects of scene movement on circular vection-induced sickness

Yang and Pei (1991), studied the vection-induced motion sickness with scene rotations in *pitch*, *yaw* and *roll* axes. Effect of head movements was also investigated. In their experiments, subjects sat on a chair with the head positioned at the center of a hollow fiberglass sphere (diameter: 2.74m). The interior of the sphere was painted randomly with black dots of diameter range from 1 to 5 cm. The highest motion sickness ratings were obtained with scene rotations in the pitch axis, followed by roll and yaw axes. Although yaw vection simulation was the strongest self motion illusion.

Hu *et al.*, (1997) studied the effects of spatial frequency of a vertically striped rotating drum on the level of vection (self-motion illusion) and the severity of vection-induced sickness. Subjects were exposed to vertically striped rotating drum with black and white strips. Five different levels of spatial frequencies have been investigated: 0.267, 0.133, 0.067, 0.033 and 0.0167cpd. The results indicated that rotating scene with 0.067cpd (4/60 cpd) would general significantly higher level of vection and motion sickness ratings.

Muller *et al.* (1990) studied the effects of pitch axis scene rotational speed on vection. Strongest subjective vection was reported when the speeds were between 50°/second to 200°/second. The latency from the start of scene rotation and the onset of vection was also studied.

2.2.2 Effects of vection combined with head movement

Lackner and Teixeira (1997) reported that yaw vection (10°/s to 80°/s within 12 minutes) combined with head movement (20cpm, shoulder to shoulder) would reduce the perception of vection and symptoms of motion sickness.

Yand and Pei (1991), studied the interaction of vection and head movements. They reported that yaw vection (45°/s) combined with pitch or roll head movements (0.5 Hz, 20°) would significant increase average scores of motion sickness symptoms. Besides they indicated that scene rotation (vection) and head movement about the same axis would significantly reduce average score of motion sickness symptom.

These two studies showed different results. The difference could be due to the difference in ranges and frequencies of the head movement.

2.2.3 Effects of human races on vection-induced sickness susceptibility

Between 1990 and 1995, Stern and his colleagues carried out many experiments on circular vection-induced motion sickness of seated subjects. Scene rotations were generated with a rotating optokinetic drum with black and white strips (drum: 91.5cm in height, 76cm in diameter; black strip: 3.8cm wide (5.7°); whitestrip: 6.2cm wide (9.3°)). All scene rotations were in yaw axis and at a speed of 60°/second. In 1993, they studied the effect of human race on motion sickness susceptibility. They reported that by comparing sickness symptom of African-American, European-American and Chinese female subjects, Chinese subjects showed significantly more severe symptoms. Reported sickness symptoms included dizziness, cold sweating, pallor, stomach awareness, and nausea.

2.2.4 Methods to reduce severity of vection-induced motion sickness

Different means to reduce the severity of visually-induced motion sickness symptoms have been reported: drug treatment (Stern *et al.*, 1994, Muth *et al.*, 1995); electrical acustimulation and P6 acupressure (Hu *et al.*, 1992, 1995); visual field restriction (to less than 15°) and visual fixation (Stern *et al.*, 1990). In addition, adaptation to vection-induced sickness symptoms was found with intersession intervals of 48 hours or less (Stern *et al.*, 1989).

Although, experiments on vection-induced motion sickness have been many (yaw axis scene rotation): Stern *et al.*, 1990, 1994, 1995, Hu *et al.*, 1992, 1995, Muth *et al.*, 1995; pitch axis scene rotation: Muller *et al.*, 1990, the effects of scene rotation axis on the severity of motion sickness have not been studied. Table 2.2 summarizes the studies on vection-induced motion sickness.

Table 2.2. Summary of studies on vection-induced motion sickness

Authors	Topics investigated	Axis of scene rotation
Stern *et al.*, 1993	Effect of human race on motion sickness susceptibility	Yaw
Stern *et al.*, 1989	Method to reduce vection-induced motion sickness	Yaw
Stern *et al.*, 1990	Method to reduce vection-induced motion sickness	Yaw
Stern *et al.*, 1994	Method to reduce vection-induced motion sickness	Yaw
Hu *et al.*, 1989	Relationship between speed of rotation of circular vection and severity level of motion sickness	Yaw
Hu *et al.*, 1995	Method to reduce vection-induced motion sickness	Yaw
Muth *et al.*, 1995	Method to reduce vection-induced motion sickness	Yaw
Muller *et al.*, 1990	Sense of presence	Pitch

2.3 Previous studies on simulator sickness using non-virtual reality displays

2.3.1 Side effects of simulator

Kennedy *et al.*, have carried out many experiments on simulator sickness in virtual environment (1993, 1994, 1995, 1996). They reported the symptoms and after effects of simulator sickness and also the gender difference in simulator sickness incidences. They added that the symptoms of simulators include nausea, eye strain, vertigo, vomiting etc. They indicated that for those having been exposed to a fly simulator compared with those who did not fly in a simulator, the decrement in postural equilibrium were significant. In addition, they pointed out that, females were more susceptible to simulator sickness than males. Furthermore, they reported that the engineering features of the simulator (e.g. motion base) might generate simulator sickness. Besides, Sharkey and McCauley (1991) explained that the condition with higher global visual flow of scene content of simulation would result in greater simulator sickness.

2.3.2 Predication of susceptibility

In 1995, Kolasinski reviewed literature about simulator sickness and identified 40 factors associated with simulator sickness in virtual environment into 3 global categories: subject, simulator and task. In 1996, Kolasinski found that sickness measured as a function of the total severity score from simulator sickness questionnaire was successfully modeled as a function of subject variables. The subject variables included age, gender, mental rotation ability and pre-exposure stability.

In 1992, Kennedy *et al.* developed a simulator sickness key for the purpose of prediction of simulator sickness. The simulator sickness key included the questions such as, asked the subjects' subjective motion sickness susceptibility, seasickness experiences and symptoms experienced etc. They reported that the simulator sickness key showed high correlation with reported sickness symptoms, and can be used as a self-test: the potential risk to develop simulator sickness when participating in a simulation.

2.3.3 Method to quantify simulator sickness

In 1993, Kennedy *et al.* developed a Simulator Sickness Questionnaire (SSQ) to quantify simulator sickness. The SSQ was derived from a motion sickness questionnaire (MSQ, developed by Kellogg *et al.*, 1965) using a series of factor analysis. They collected the data from 10 Navy simulators including more than 1100 MSQs data. The original MSQ contained 28 symptoms, but the SSQ contained only 16 items. The 16 symptoms were divided into three sub-scales: Nausea, Oculomotor and Disorientation. In addition, there was a Total severity measure (Total sickness score). They reported that by using the SSQ to measure the simulator sickness, side effects produced by different virtual reality or simulator systems could be compared. Nowadays many studies of simulator sickness and cybersickness use the SSQ to measure sickness (Regan and Price, 1993 & 1995; Rich and Braun, 1996; Costello and Howarth, 1996 & 1997;

Finch and Howarth, 1996; Kennedy *et al.*, 1996; Kolasinki, 1996; Bliss *et al.*, 1997; Enlrich, 1997; Stanney and Kennedy, 1997; Wilson *et al.*, 1997).

2.4 Previous studies on cybersickness with head-mounted virtual reality displays

2.4.1 Effects of duration

Finch and Howarth (1996) reported that subjects participating in a virtual reality shooting game called 'heretic' with 20 minutes exposure, have increased sickness ratings with increasing exposure duration.

Regan and Price (1993a) indicated that subjects navigating through a virtual corridor with rooms and pick up virtual objects using a 3D mouse with a helmet-mounted display could experience cybersickness. The sickness ratings significantly increase with immersion duration up to 20 minutes.

In 1994, So and Griffin reported that passive viewing of a simulated flight with controlled head movement in yaw axis with GEC Mono-CRT HMD would generate cybersickness. They reported that nausea ratings increased significantly with exposure duration.

In conclusion, exposure to VR simulation with head-coupled VR display would lead to cybersickness. The increase of cybersickness is linked to exposure duration.

2.4.2 Types of displays used

Costello and Howarth (1996) reported that conditions with VR games viewed on head-mounted display would produce higher visual fatigue symptoms than VR games viewed on a desktop monitor. Subjects who participated in the condition with VR games viewed on head-mounted display suffered higher symptoms of general discomfort, sweating, nausea, and disorientation than those who participated the VR game viewed on a desktop monitor.

In 1997, Howarth and Costello studied the effect of display type on the sickness symptoms. In their experiment, subjects were asked to play a VR chess game for one hour, the display equipment could be a desktop monitor or a virtual i-glass^{TM} headset (HMD). The results indicated that conditions with HMD produced higher sickness symptoms than those with desktop monitor. The most frequently reported symptom was eye strain.

Rich and Braun (1996) conducted an experiment to study the active control on the level of cybersickness. The task in the experiment was that subjects need to use a joystick to navigate through a virtual maze. The virtual environment was presented to the subjects via a CybersickMaxx LCD HMD and the head tracking system was enabled in the yaw axis only,. The result reported that sickness symptoms increased with both active control and the use of head tracking.

Wilson *et al.*, (1997) compared the sickness symptom between two conditions with different displays. Subjects were asked to play a duck shooting game presented via a virtual i-glass headset (HMD) or a desktop display. They reported that the use of HMD as the display apparatus resulted in significantly higher ratings on sickness symptom than the use of desktop display.

2.4.3 Effects of display field of view (FOV), stereoscopic display and auditory cues

DiZio and Lackner (1997) have studied the effect of display's field of view (FOV) on cybersickness. In their experiment subjects would passively view of an ocean with shorelines to the right, left and rear. They reported that, halving the FOV would reduce the sickness ratings by half.

In 1997, Enrlich reported that stereoscopic condition was more nauseogenic than biocular condition. He summarized and drew the above conclusion after having conducted an experiment. In the experiment the tasks included navigation, distance estimation, manual tracking and manual manipulation.

Wilson *et al.*, (1997) studied the effect of auditory cues on the level of sense of presence. They compared the sense of presence between 'with' and 'without' sound in a virtual duck shooting game. They reported that the addition of auditory cues did not affect the sense of presence. On the other hand, they indicated that there was a positive correlation between the sense of presence and sickness symptom ratings.

2.4.4 Effects of gender and user's posture

Some studies have reported that females were more susceptible to cybersickness than males. Studies include the work of Regan and Price (1993), Kolasinski (1996), and Rich and Braun (1996). Regan hypothesized that the gender difference may be due to the hormones. Besides, Regan (1993) indicated that there was no significant effect on nausea rating between sitting and standing subjects. Furthermore, Regan reported that mis-match between the inter-pupillary distance and the head-mounted display can lead to more oculomotor related problem.

2.4.5 Effects of time lag and head movements

So and Griffin (1994) reported that an imposed 280ms time lag to a passive viewing of a flight simulation (20 minutes duration) with controlled head movement in yaw axis did not increase the nausea ratings. Besides they studied the effect of additional yaw head movements (0.015-0.025 Hz) on nausea rating. They indicated that addition of yaw head movements with low frequency would not affect the nausea ratings. Further they found that the rated level of realism of the virtual environment was significantly correlated with symptoms of nausea ratings.

On the other hand, DiZio and Lackner (1997) indicated that passive viewing of a virtual environment with an imposed time lag (from 67ms to 367ms) would increase the sickness ratings linearly. During the experiment, subjects had to made 24 discrete head movements with amplitude 18° to 180°.

The differences in the results of these two studies could be due to the differences in nature of the tasks, types and speeds of head movements, ...etc.

2.4.6 Methods to reduce cybersickness

In 1995, Regan studied the effect of repeated immersion on symptoms of cybersickness. Regan reported that for intersession less than one week between repeated immersion, the decrease of reported sickness symptoms changed obviously. The decrease in malaise was based on the suggestion of simulator sickness literature, it stated that for intersessions less than one week, the sensitization would decrease. Besides, Regan indicated that drug treatment (Hyoscine) could reduce nausea and other sickness symptoms.

In 1998, Harris *et al.* reported that the presence of vestibular cues has a significant effect on a virtual reality operator's estimating of self-motion, and this method was believed that it could reduce cybersickness.

Chapter 3 Lessons from literature review

3.1 Main findings of the past studies

A review of literature indicates that the uses of virtual reality systems can cause cybersickness. This has been confirmed by many studies (e.g. Regan, 1993, 1995; Enrlich, 1997; Wilson *et al.*, 1997; DiZio and Lackner, 1997). Many factors affecting how visual scene is presented during a simulation can influence the level of cybersickness. These factors include display field of view, stereoscopic display, time lag and head movements. Cybersickness is mainly due to visually-induced factors. This suggests that visual stimuli could affect the rated level of cybersickness.

Previous studies have focused on the factors affecting how scene movement is presented rather than what is being presented. The former includes static factors like FOV and stereoscopic display. The later includes dynamics factors like visual scene movement.

3.2 Problems with previous research and alternative approaches

3.2.1 Lack of understanding concerning the effect of scene movement in different axes

Although studies concerning cybersickness have been reported, studies investigating the fundamental variables such as scene rotational axes were not found. In order to determine the cause of sickness, a study of the effects of scene movement in different axes is necessary. In addition, there was no experimental study to isolate the effects of scene movement on rated level of cybersickness. As discussed later in the thesis, an experiment has been conducted to investigate the effects of scene oscillation on the rated level of cybersickness.

3.2.2 Lack of a quantitative tool to quantify visual stimuli

Cybersickness is a type of visually-induced motion sickness, as many studies have reported before. This indicates that visual stimulus is one of the main cause of cybersickness. Visual stimuli can be referred to the scene movement perceived by a VR user during the whole simulation session. This can have two main component: (i) the content or complexity of the scene, and (ii) the movement of the scene relative to the users. However up to now, there is no systemic method to measure visual stimuli of virtual reality simulation. So, the formulation of a new method to quantify visual stimuli of a virtual environment simulation is desirable. Since the visual stimuli contain information of visual content and visual scene movement, it is necessary to measure the visual scene content and visual scene movement of the virtual reality simulation first. After that, the measurement of visual stimuli can be proposed. A method to quantify visual stimuli in a virtual environment simulation is presented later in this thesis. Two experiments have been conducted to verify the effects of the key components (namely, scene complexity and scene velocity) on level of cybersickness. The results of these experiments indicate that the newly proposed method is an appropriate measurement to quantify visual stimuli in a virtual environment simulation.

Chapter 4 Method to quantify scene content in virtual environment

4.1 Use of scene complexity to quantify scene content

The term scene content is too extensive, an alternative term – scene complexity is more specific to describe the visual scene of a virtual environment. Furthermore, studies on vection-induced motion sickness with rotating image indicate that the use of color, patterns, and perspective view have no significant effect on the level of sickness. The general conclusion is that vection-induced sickness is mainly affected by the spatial complexity of the moving image. In this study, we would focus on the spatial complexity first. The author of this thesis does not intend to rule out the influence of color and meaning of the scene. However, this will be part of the future work and is outside the scope of this study.

4.2 Definition of spatial complexity of a scene

Barfield *et al.*, studied the relationship between scene complexity and perceptual performance for computer graphics simulations (1990). In their study, they used total number of objects and homogeneous of colors to define the level of scene complexity.

In the field of image digital processing industrial, the use of spatial contrast information to describe an image has been largely used. The term 'spatial frequency' is used to quantify the contrast information (changes in luminance levels per degree).

Besides the use of 'spatial frequency', visual scene pattern can be described in terms of contrast ratio. The meaning of contrast is the luminance difference between an object and its background. The difference in luminance is called relative contrast. For example, an object with a luminance of level L_O in a background of luminance level L_B has a contrast ratio of:

$$\frac{(L_B - L_o)}{L_B} = \frac{\Delta L}{L_B}$$

For periodic stimuli (e.g. sine wave gratings or square wave grating), Michelson contrast C_m can be used:

$$C_m = \frac{(L_{max} - L_{min})}{(L_{max} + L_{min})}$$

Where L_{max} is the maximum luminance in the pattern, L_{min} is the minimum value. Although contrast ratio can be used to describe the complexity of a visual pattern, it cannot describe the changes in luminance levels spatially. On the contrary, spatial frequency (number of luminance cycle per visual degree) contains both the luminance and spatial information. If contrast ratio has to be used, the whole picture will need to be divided into many small regions so that the contrast ratio of each region can be calculated. The changes in the contrast ratios across the spatial region will then be calculated. Since there is no standard method for performing the above calculations, the 'spatial frequency' is used instead of contrast ratio. The author does not wish to discount the usefulness of contrast ratio, future studies comparing the use of contrast ratio and spatial frequency are desirable.

In this study the term 'spatial frequency' is used to quantify scene complexity. The higher the value of the 'spatial frequency', the higher the level of scene complexity and vice versa. The unit of spatial frequency is cycles of alternation of luminance per visual degree (cyc/deg). Figure 4.1a illustrates an alternative black and white strip pattern. The spatial frequency of this figure is 0.2 cyc/deg. Figure 4.1b illustrates a relatively thin bars (covering the same visual angle) than that in Figure 4.1a. The spatial frequency of Figure 4.1b is 0.4 cyc/deg. Visually, Figure 4.1b is more complex than Figure 4.1a, and the spatial frequency of Figure 4.1b is higher than that of Figure 4.1a.

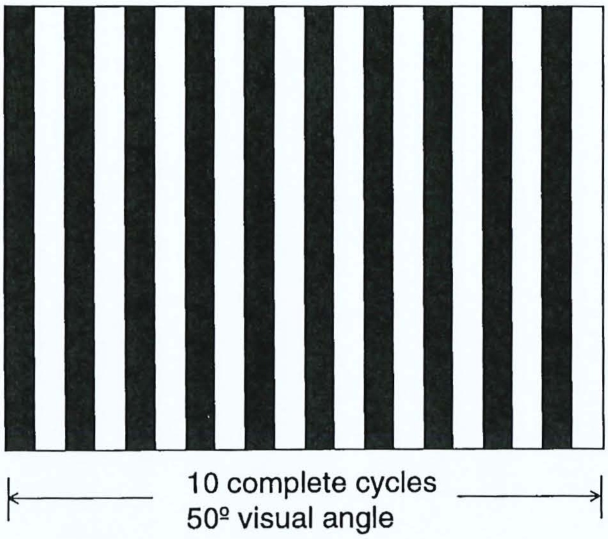


Figure 4.1a

Alternative black and white strips pattern with 10 complete cycles cover a 50° visual angle

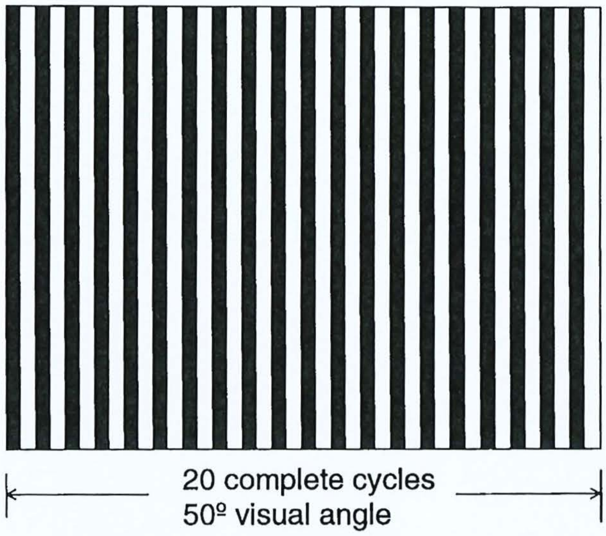


Figure 4.1b

Alternative black and white strips pattern with 20 complete cycles cover a 50° visual angle

Figures 4.1a and 4.1b just illustrate the spatial frequencies of the patterns in the horizontal axis. If an image shows a much more complex image (e.g. Figure 4.2), it can be described by spatial frequencies in three axes. The three values are (i) the average horizontal spatial frequency ($SF_{horizontal}$); (ii) the average vertical spatial frequency ($SF_{vertical}$); and (iii) the average radial spatial frequency (SF_{radial}). The average radial spatial frequency (SF_{radial}) is the geometrical sum of the average horizontal spatial frequency ($SF_{horizontal}$) and the average vertical spatial frequency ($SF_{vertical}$) (see Equation 4.1).

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

Equation 4.1

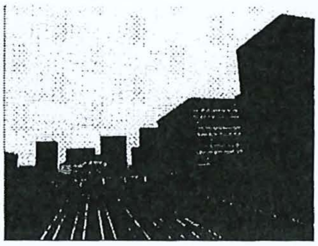


Figure 4.2 A City snapshot from a virtual environment simulation

4.3 Method to calculate the spatial frequencies of a dynamic virtual environment

4.3.1 Take five representative snapshots of the dynamic virtual environment

Since when calculating spatial frequencies, this applies to still patterns. Therefore when considering a dynamic virtual environment, it is necessary to take several representative still pictures of it. Suppose the dynamic virtual environment is a 30 minute virtual guided tour simulation, and then choose five snapshots that can represent the path of the virtual guided tour (steps to capture a picture in an

Onyx workstation is shown in Appendix G). For the ease of explanation, the pictures in Figure 4.3 have been assigned as Picture I, Picture II, Picture III, Picture IV and Picture V.

4.3.2 Algorithms of measuring spatial frequencies of a dynamic virtual environment

4.3.2.1 Gray scale extraction

The spatial frequencies of the five captured pictures will be calculated individually. Flowchart 4.1 illustrates the steps in calculating the spatial frequencies. First, it is necessary to store the pictures in a format contains the gray scale information of each pixel of the pictures. The gray scales of each pixel are then extracted.

The range of the gray scale goes from 0 to 255. The numerical value 0 represents 'black' while the numerical value 255 represents 'white' (the full range of gray scale is shown in Appendix S). The gray scale of each pixel is an indication of the luminance level of that pixel. In addition, the information is stored in ASCII format. A file format called – portable graymap file format 'pgm' is used (steps to store a picture in 'pgm' format in an Onyx workstation is illustrated in Appendix H)

4.3.2.2 Edge elimination

A C++ program (see Appendix I) has been developed to extract the gray scale of each pixel of the pictures. Before calculating the spatial frequencies of the pictures, the edges of the pictures should be eliminated first. As some back lines in the edges of the picture may be introduced during the procedure of capturing a picture. These black lines could affect the values of spatial frequencies. By trial and error, the width of the black lines are usually less than 3 pixels, so it is appropriate to cut 1% pixels in top, bottom, left and right sides of the picture and rescale the corresponding FOV respectively. For example, a picture with dimension 640 (horizontal) × 480 (vertical) pixels and the field of view is 48° (horizontal) × 36° (vertical), the new dimensions and the corresponding FOV after the elimination are 627 (horizontal) × 470 (vertical) pixels and 47° (horizontal) × 35° (vertical) respectively.

4.3.2.3 Spatial frequency calculation of each row

Firstly, let's focus on Picture I of Figure 4.3. The gray scales values of each row can be treated as a series of numbers and the average frequency of this series of numbers will be calculated. This frequency will be the spatial frequency (SF) of that particular row and is referred to as $SF_{row(i)}$ (where i refers to the number of the row) The average spatial frequency of each row indicates how the luminance level changes spatially across each row. If the entire row has only one luminance level, then the series of gray scale numbers of that row will be a serious of constant numbers and the spatial frequency of that row will be zero.

4.3.2.4 Spatial frequency calculation of each column

The same method is applied to calculate the spatial frequency of each column, $SF_{column(j)}$ (where j refers to the number of the column) The average spatial frequency of each column indicates how the luminance level changes spatially across each column.

4.3.2.5 Average spatial frequency of one picture

The same procedures are repeated to calculate all the average spatial frequencies of all rows. The average horizontal spatial frequencies of Picture I ($SF_{horizontal\text{-}Picture\ I}$) is the average of the values of the spatial frequencies of the rows. The same method is applied to calculate the average vertical spatial frequency of Picture I ($SF_{vertical\text{-}Picture\ I}$) Besides, the radial spatial frequency of Picture I ($SF_{radial\text{-}Picture\ I}$) is the geometrical sum of the average horizontal spatial frequency ($SF_{horizontal\ Picture\ I}$) and the average vertical spatial frequency ($SF_{vertical\ Picture\ I}$).

4.2.3.6 Average spatial frequency of a virtual simulation

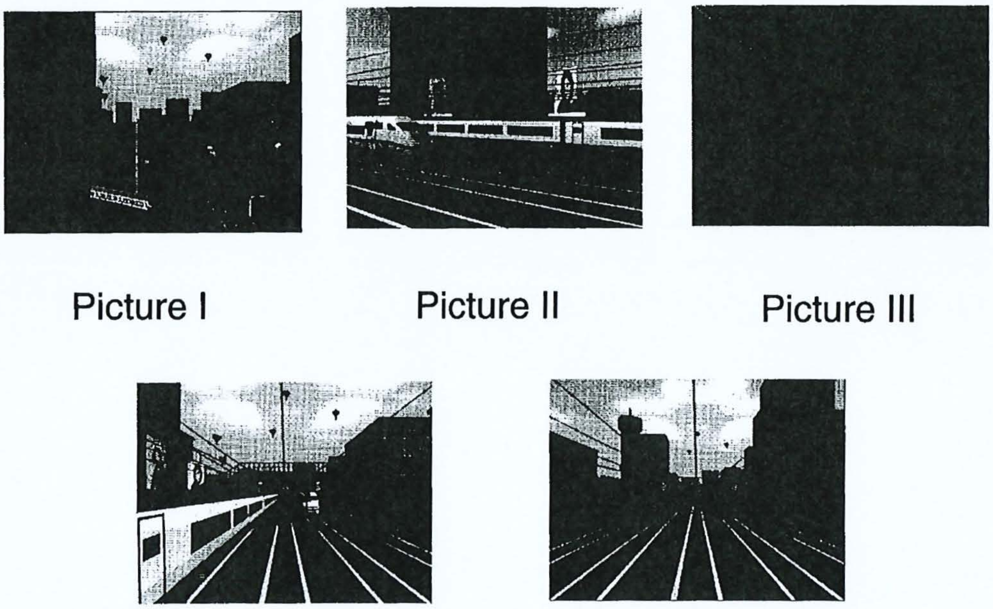
Similarly, the average horizontal, vertical and radial frequencies of Picture II, Picture III, Picture IV and Picture V can be obtained by the same method. Finally, the average values of these five pictures can be used to represent the three axes spatial frequencies of the dynamic virtual environment simulation. The spatial frequencies of the virtual environment represent the luminance level changes spatially over the whole simulation

4.3.2.7 Program written to automate the spatial frequency calculation

A METLAB batch file is used to calculate the average horizontal, vertical and radial spatial frequencies of a picture. The programming code is as shown in Appendix J.

4.4 A case illustration: the spatial frequencies of an example virtual environment simulation

The example simulation consists of 30 minutes navigation through in a virtual city. Five representative snapshots of this simulation are presented in Figure 4.3. Table 4.1 summarizes the spatial frequencies of individual picture and that of the dynamic virtual environment. The steps to calculate the spatial frequencies of a dynamics virtual environment simulation are shown in Appendix T



Picture I Picture II Picture III

Picture IV Picture V

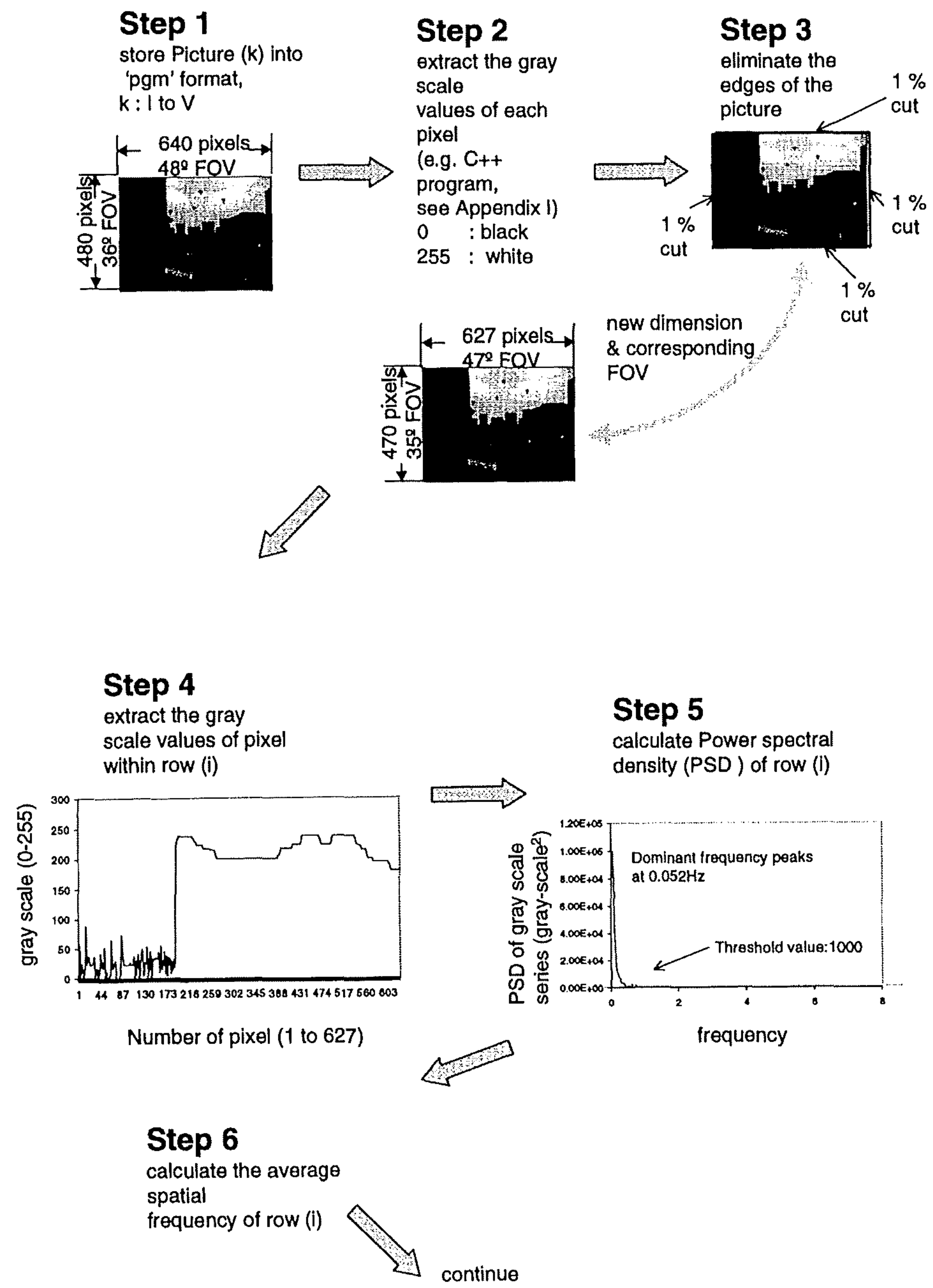
Figure 4.3 Five representative snapshots of a virtual flight simulation in a city

Table 4.1 Average horizontal, vertical and spatial frequencies of five snapshots and the whole virtual environment simulation (30 minutes duration)

	Average horizontal spatial frequency	Average vertical spatial frequency	Average radial spatial frequency
Picture I	0.1816	0.1123	0.2135
Picture II	0.1110	0.0725	0.1326
Picture III	0.0627	0.0743	0.0972
Picture IV	0.1214	0.1949	0.2296
Picture V	0.3011	0.2152	0.3701
Whole virtual environment	0.1556	0.1339	0.2086

The following chart (Flow chart 4.1) illustrates the steps to calculate spatial frequencies of the virtual environment.

Flow chart 4.1 illustration of the steps to calculate the three axes spatial frequencies of the virtual environment



Step 7

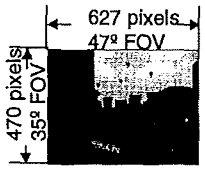
repeat **Step 4** to **Step 6** to calculate the average spatial frequencies of the other rows (i from 1 to 627)

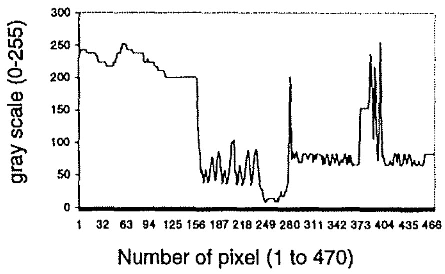
Step 8

calculate the average horizontal spatial frequency of the picture

Step 9

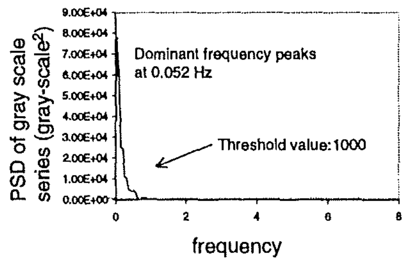
extract the gray scale values of pixels within column j





Step 10

calculate Power spectral density (PSD) of column (j)



Step 11

calculate the average spatial frequency of column

continue

Step 12
repeat **Step 9** to **Step 11** to calculate the average spatial frequencies of the other columns (j from 2 to 470)

Step 13
calculate the average vertical spatial frequency of the picture

Step 14
calculate the average radial spatial frequency of the picture

Step 15
Repeat **Step 1** to **Step 14** to calculate the horizontal, vertical and radial spatial frequencies of Picture 2, Picture 3, Picture 4 and Picture 5

Step 16

Spatial frequencies of the dynamic dynamics are the average of the 5 pictures respective

(i) average horizontal spatial frequency, $Sf_{horizontal}$
(ii) average vertical spatial frequency, $SF_{vertical}$
(iii) average radial spatial frequency, SF_{radial}

Chapter 5 Methods to quantify scene movement velocity

5.1 Definition of scene movement

Usually, in a typical immersive virtual reality simulation, the simulation is presented on a head-mounted display. When users move their heads, the scene of the virtual environment will be updated according to the users' head orientations. In order to navigate through a virtual environment, the users can use some navigation tools (e.g. 3D mouse) control the direction of travel, or there will be a fixed path (pre-determined by the virtual reality program) to lead through the virtual environment. Basically the visual scene movement is the sum of head movement and the object movement.

5.2 Method to quantify scene movement velocity

The term 'viewpoint' refers to the vector from which a user will see the computer-generated virtual world. This can be understood as the viewpoint of a virtual camera whose captured image will be the visual scene presented to the users. During a VR tour, this viewpoint changes and resulting in a moving scene. The coordinate system of the viewpoint contains x (fore-and-aft), y (lateral), z (vertical) positions and pitch, yaw and roll orientations. By recording the 6 values of the viewpoint over the whole exposure time of the simulation, the displacement curves in the 6 axes can be obtained. By differentiating the displacement curves with respect to time, the velocity curves in the 6 axes are obtained. Finally, the root mean square (r.m.s) values of the 6 velocity curves are used (use V_x, V_y, V_z, V_{pitch}, V_{yaw} and V_{roll} to represent).

5.3 A case illustration: the scene velocities of an example virtual environment simulation

The previous chapter (Chapter 4) has discussed how to calculate the spatial frequencies of a virtual guided tour simulation. In particular, section 4.4 documents the spatial frequencies of an example virtual environment. Table 5.1 summarizes the scene velocities of a virtual guided tour through that particular virtual simulation. The displacement and velocity time history curves of the viewpoint vectors in 6 axes throughout the simulation are shown in Appendix O.

Table 5.1 Scene velocities (r.m.s.) in 6 axes of a particular virtual tour through a virtual environment with 30 minutes duration

Moving axis (unit)	r.m.s scene velocity
x-axis (fore-and-aft) (m/s)	9.5944
y-axis (lateral) (m/s)	3.1137
z-axis (vertical)(m's)	0.5919
Roll-axis (degree/s)	1.4143
Pitch-axis (degree/s)	1.6331
yaw-axis (degree/s)	10.9898

Chapter 6 Use of spatial velocity to quantify visual stimuli in a virtual environment simulation

6.1 Method and algorithms to calculate spatial velocity

As mentioned before, the visual stimuli have two main components: (i) visual scene content and (ii) visual scene movement. In the previous two chapters the methods to measure and quantify visual scene content (with spatial frequencies) and scene movement velocity have been discussed. This chapter will present a method to combine spatial frequency and scene movement velocity to represent the visual stimuli.

The term 'spatial velocity' (SV) has been invented to quantify visual stimuli in a virtual environment simulation. The definition of 'spatial velocity' is the rate of change of contrasted information. The contrasted information is determined by spatial frequency (i.e. the scene complexity), the rate is determined by scene movement velocity. The following equation (see Equation 6.1) can be used to describe this relationship.

$$\text{Spatial velocity} = \text{Spatial frequency} \times \text{Scene movement velocity}$$

Equation 6.1

Logically, the 'spatial velocity' can be decomposed into six axes: x (fore-and-aft), y (laterally), z (vertically), roll, pitch and yaw axes (use SV_x, SV_y, SV_z, SV_{roll}, SV_{pitch}, SV_{yaw} to represent). 'Spatial velocity' in a particular axis is defined as the product of the scene movement velocity and the spatial frequency along that axis. The only exception is SV in fore-and-aft axis. Spatial frequency in radial axis is used because during fore-and-aft motion, a user will perceive movement of spatial patterns in both horizontal and vertical directions. The following matrix (Equation 6.2) shows the calculation of the 'spatial velocity' in 6 axes.

For example, $SV_{yaw} = V_{yaw} \times SF_{horizontal}$. Table 6.1 summarizes the equations of the 'spatial velocity' in 6 axes.

$$\begin{pmatrix} SV_x & Sv_{roll} \\ SV_y & SV_{yaw} \\ SV_z & SV_{pitch} \end{pmatrix} = \begin{pmatrix} V_x & V_y & Vz \\ V_{roll} & V_{yaw} & V_{pitch} \end{pmatrix} \times \begin{pmatrix} SF_{radial} & 0 & 0 \\ 0 & SF_{horizontal} & 0 \\ 0 & 0 & SF_{vertical} \end{pmatrix}$$

Equation 6.2

Table 6.1. The six axes equations of spatial velocity

Spatial velocity in a particular axis	The corresponding scene movement velocity	The corresponding perceived spatial frequency	The corresponding Equation
x-axis (fore-and-aft), SV_x	In x-axis , V_x	Average radial spatial frequency, SF_{radial}	$SV_x = V_x \times SF_{radial}$. Equation 6.3
y-axis (lateral,) SV_y	In y-axis, V_y	Average horizontal spatial frequency, $SF_{horizontal}$	$SV_y = V_y$ x $SF_{horizontal}$ Equation 6.4
z-axis (vertical), SV_z	In z-axis, V_z	Average vertical spatial frequency, $SF_{vertical}$	$SV_z = V_z \times SF_{vertical}$ Equation 6.5
Roll-axis, SV_{roll}	In roll-axis, V_{roll}	Average radial spatial frequency, SF_{radial}	$SV_{roll} = V_{roll} \times SF_{radial}$ Equation 6.6
Pitch-axis, SV_{pitch}	In pitch-axis, V_{pitch}	Average vertical spatial frequency, $SF_{vertical}$	$SV_{pitch} = V_{pitch} \times SF_{vertical}$ Equation 6.7
Yaw-axis, SV_{yaw}	In yaw-axis, V_{yaw}	Average horizontal spatial frequency, $SF_{horizontal}$	$SV_{yaw} = V_{yaw} \times SF_{horizontal}$ Equation 6.8

6.2 A case illustration: the spatial velocity of an example virtual environment simulation

How to calculate the spatial frequencies and scene velocities of an example virtual guided tour simulation have been discussed in sections 4.4 and 5.3 respectively. Table 6.2 summarizes the spatial frequencies, scene velocities and 'spatial velocities' of this particular virtual simulation.

Table 6.2. The values of scene velocities, spatial frequencies and spatial velocities of a particular virtual simulation with 30 minutes duration

Scene movement velocity	Spatial frequency	Spatial velocity
In x-axis , $V_x = 9.5944$	Average radial spatial frequency, SF_{radial}.= 0.2086	$SV_x = 2.0014$
In y-axis, $V_y = 3.1137$	Average horizontal spatial frequency, $SF_{horizontal} = 0.1556$	$SV_y = 0.4844$
In z-axis, $V_z = 0.5919$	Average vertical spatial frequency, $SF_{vertical} = 0.1338$	$SV_z = 0.0792$
In roll-axis, $V_{roll} = 1.4143$	Average radial spatial frequency, SF_{radial}.= 0.2086	$SV_{roll} = 0.2950$
In pitch-axis, $V_{pitch} = 1.6331$	Average vertical spatial frequency, $SF_{vertical} = 0.1338$	$SV_{pitch} = 0.2186$
In yaw-axis, $V_{yaw} = 10.9898$	Average horizontal spatial frequency, $SF_{horizontal} = 0.1556$	$SV_{yaw} = 1.7096$

Chapter 7 Studies of effects of scene oscillation axes on cybersickness with a head-coupled virtual reality system (Experiment one)

7.1 Purpose of the experiment

One of the reasoning behind the development of the 'spatial velocity' metric is that visual scene movement is a major contribution factor towards cybersickness generation. This experiment will investigate the effects of adding visual scene movement in different axes to the rated level of cybersickness.

7.2 Objective and hypotheses

An experiment was conducted to study the effects of scene oscillations on cybersickness. The objective was to determine the relationship between axes of visual scene oscillation and the rated level of cybersickness. It is hypothesized that (i) visual scene oscillation in the pitch axis will produced higher rated level of cybersickness than scene oscillations in the yaw and roll axes; (ii) virtual environment without scene oscillations would produce lower level of sickness. The former hypothesis is base on Griffin (1991). He suggested that due to gravitational force, head pitch movement may produce a stronger stimulus to the vestibular system than the head yaw movement. In 1971, Benson and Guedy reported that pitch axis head oscillations would produce higher levels of sickness incidence when compared with yaw axis head oscillations. Lawther and Griffin (1986,1988) proposed that low frequency (about 0.2 Hz) whole-body oscillations in pitch and the vertical axes were statistically correlated with seasickness incidence. Head movements in pitch and roll are much more nauseogenic. Some measurements of vessel motion and consequent seasickness amongst passengers reported that the vomiting incidence and illness were linearly related to the vertical z-axis acceleration (Griffin *et al.*, 1988). In addition, rotation about off-vertical axis (z-axis) of car motion can cause symptoms of motion sickness. If human respond differently to physical oscillations in different axes, then it is hypothesized that human will also respond differently to scene oscillation of different axes.

7.3 Dependent and independent variables

In this study, three independent variables were used: (i) duration of exposure to virtual reality simulation (0 to 20 minutes); (ii) scene oscillation directions (oscillation in pitch, yaw and roll axes); and (iii) with and without scene oscillation. This design was consistent with previous studies on cybersickness (Regan and Price (1995), So (1994)).

During the simulation, the visual scene would oscillate at a constant angular velocity (Figure 7.1). The range of scene oscillation was chosen to be 120°

(±60°) because this is appropriate to the normal range of neck rotation and flexion (right, left, dorsal and ventral) are not more than 120° (Figure 7.2). In addition, this range of oscillation is expected in a typical virtual reality simulation. An angular velocity of 30° per second was used and the frequency of scene oscillation was 0.125Hz.

up	straight ahead	down
+60°	0°	-60°

Figure 7.1a Snapshots illustrating the scene oscillation in pitch axis

left	center	right
+60°	0°	-60°

Figure 7.1b Snapshots illustrating the scene oscillation in yaw axis

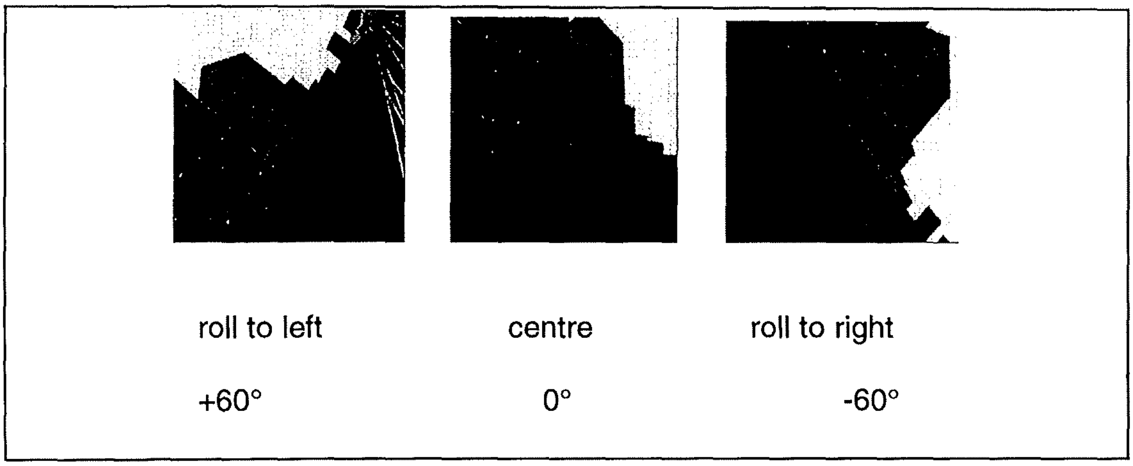
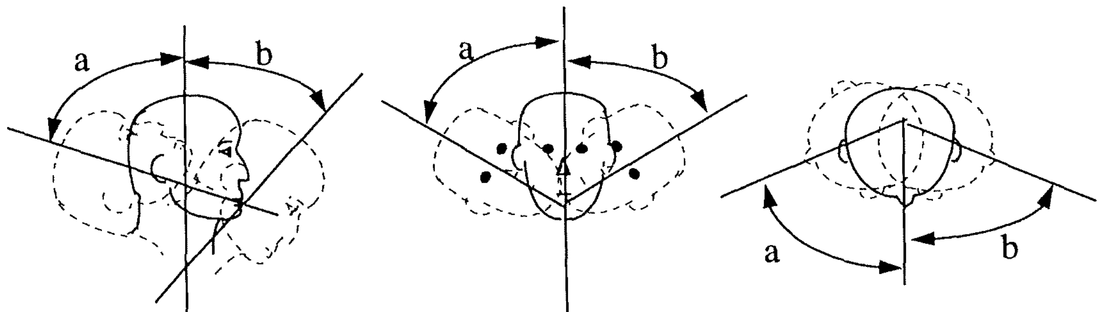


Figure 7.1c Snapshots illustrating the scene oscillation in roll axis



Neck Flexion, dorsal (a)
ventral (b)

Neck Flexion, right (a)
left (b)

Neck rotation, right (a)
left (b)

Figure 7.2 Maximum range of neck motion

The simulation took place in a darkened environment so that the only visual stimulus came from the VR4 head-mounted display. The laboratory was air-conditioned in order to eliminate the temperature and ventilation variables. The temperature of the room was kept at about 23°C and the relativity humidity was about 58%. During the twenty minutes simulation, subjects could hear a white noise of 60 dBA via the head phone of the head-mounted display.

The dependent variables were: (i) level of sickness rating; (ii) sickness symptoms and (iii) rated realism of simulation. A motion sickness history questionnaire (Appendix A) was used to estimate subjects' susceptibility of motion sickness. The questionnaire has been used in previous studies (So, 1994).

Before the simulation, subjects were asked to complete a symptom checklist containing 27 items (adapted from Kennedy *et al.*, 1993, see Appendix B). After the simulation, subjects were required to fill out this checklist again to compare reported symptoms before and after the simulation. Examples of symptoms included: 'general discomfort'; 'fatigue'; 'headache'; 'eyestrain'; 'sweating' and 'nausea'. These symptoms were associated with four levels of severity: (i) none, (ii) slight, (iii) moderate, and (iv) severe. Other symptoms such as blurred 'vision'; 'stomach awareness' and 'vertigo' were given a choice of 'yes' and 'no'.

A seven point subjective rating scale was used to measure the level of unpleasant feeling during the simulation (see Appendix C). This scale ranged from 'no symptom' to 'moderate nausea' scale. After the twenty minutes experiment, the realism of the virtual environment was measured using a simulation assessment questionnaire (modified from Regan and Price, 1993a, Appendix D).

7.4 Apparatus and VR software

The simulation was developed using a virtual reality authoring software (dVISE) running on a Silicon Graphics ONYX workstation. The general arrangement of experimental apparatus is presented in Figure 7.3. A Polhemus 3-SPACE magnetic tracker was used to measure head position and orientation at 30 samples per second. This tracker was mounted on top of a head-mounted display (FOV of VR4 head-mounted display: 48° horizontal 36° vertical).

Same visual scenes were presented to both eyes and the images completely overlaid each other (i.e. biocular images). The images were focused around at two feet in front of the display and were continuously updated according to head orientation at 30 frames per second. The weight of the head-mounted display was 0.935kg and the pixel resolution was 742 (horizontal) 230 (vertical).

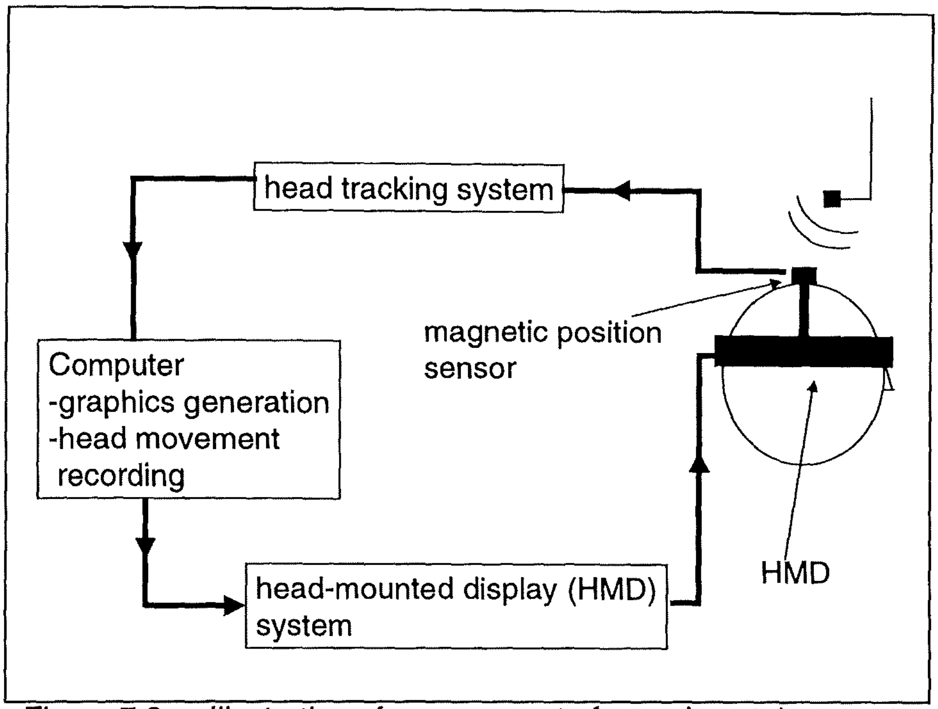


Figure 7.3 Illustration of arrangement of experimental apparatus

7.5 Visual scene content of the simulation

During the twenty minutes simulation, the visual scene consisted of some buildings, several railways, grassland, a train station and a blue sky (Figure 7.1). In this study the visual scene would either be space stationary (a control condition) or oscillate in the pitch, yaw or roll axes. The axis co-ordination is illustrated in Figure 7.4.

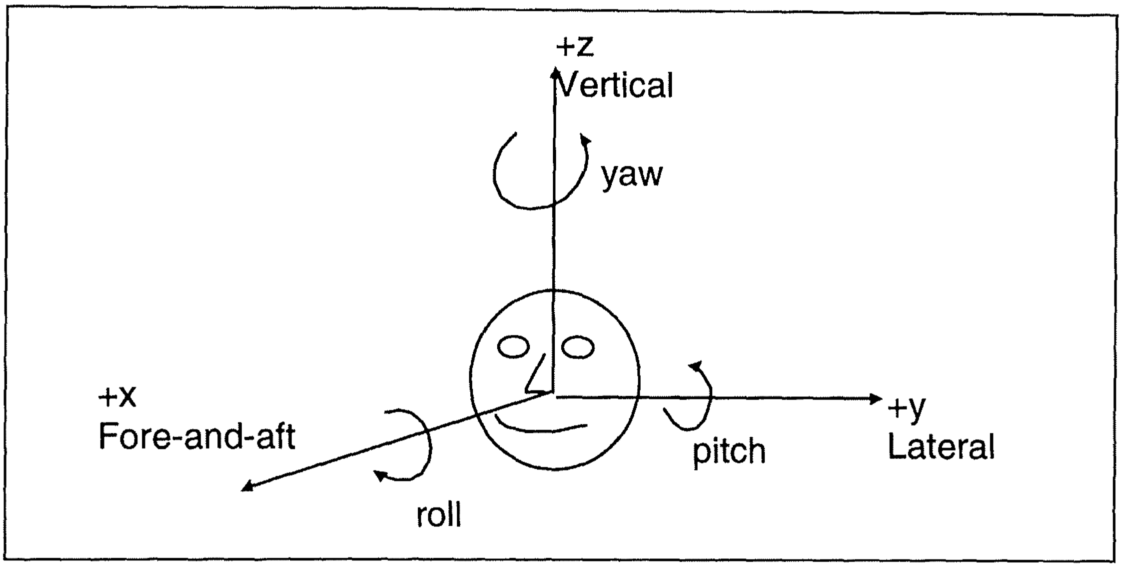


Figure 7.4 Illustration of the three rotational directions

7.6 Method and Design

Sixteen male Chinese volunteers participated in the experiment. They were staffs and students at the Hong Kong University of Science and Technology (age: 19 to 39; mean = 26). Four conditions were investigated in this experiment: scene oscillations in pitch, yaw, and roll axes and no oscillation. During each condition, subjects would be exposed to a twenty minutes virtual reality simulation. Before the subjects participated the experiment, they were asked to complete a motion sickness history questionnaire. All subjects participated the four conditions with an interval not less than 7 days between each condition. The orders of presenting the conditions were balanced with four 4 4 Latin squares design. Also, for the same subject, the time of each simulation was kept approximately the same (e.g. if the subject was exposed to the first simulation at 11:00 a.m., he would be exposed to the second simulation also at 11:00 a.m. a week later). All subjects received a sum of HK$200 to compensate for their time.

The experimental procedure were consistent with So (1994) and Regan (1995). The sixteen subjects were briefed about the experiment and were then asked to read and sign a consent form. They were informed that they could withdraw from the experiment at any time on request and under no obligation to give reasons for withdrawal or to attend again for experimentation. At the beginning of the experiment, subjects were asked to rest for five minutes to minimize any unwanted influence from any previous activities. The subjects were then required to complete a 'sickness symptom checklist', adapted from Kennedy *et al.*, (1993) (see Appendix B). The inter pupillary distance of the subjects was measured prior to their data sessions so that the distance between left and right display of the head-mounted display (HMD) could be adjusted accordingly. Subjects would then put on the HMD and one minute practice was given to the subjects to familiarize themselves with the equipment. During this one minute practice, subjects were allowed to move their heads to inspect the virtual environment that they were 'immersed' in, but during the twenty minutes simulation, they were asked to keep their head steady in a straight ahead position. Subjects remained seated throughout the simulation. The chair they sat had a back-rest, a lumber support and two arm-rests. Before the simulation, the height of the chair was adjusted according to the subjects' preference. In this study, the scene motions were controlled during the 20 minutes of the simulation (scene oscillation in pitch, yaw or roll direction as well as a control condition with no scene movement). At five-minute intervals from the start of the simulation, subjects were verbally asked to rate their symptoms of nausea on a seven-point nausea scale (see Appendix C). After the simulation session, the subject were asked to complete another 'sickness symptom checklist' and a 'simulation assessment questionnaire' (Appendix D).

7.7 Results and discussion

7.7.1 Result of sickness rating and symptoms between with and without scene oscillation conditions

7.7.1.1 Effect of scene movement on nausea ratings

A two factor (scene movement * duration) analysis of variance (ANOVA) was performed on the variance scores of nausea ratings for each. There was significant interaction between the two factors. In the with scene movement and without scene movement conditions, the nausea ratings increased with duration, but the rate of increase in the nausea ratings of the with scene movement condition was higher than that of the without scene movement condition ($F(4,310)=7.82$, $p=0.0001$, see Appendix F: Table F.1) This analysis showed that by comparing the control condition (without scene movement) with the other three conditions (scene oscillation in pitch, yaw and roll axes), there was a significant difference between the nausea ratings (F(1,310)=107.88, p=0.001, see Appendix F: Table F.1). Post-hoc Student Newman Keuls (SNK) test showed that the mean nausea rating of the 'with' scene movement condition was 0.95417, while the value of the 'without' scene movement condition was 0.2000 (see Appendix F: Table F.2). This indicated that scene movement might cause higher nausea ratings (vection-induced sickness). It may because in the with scene movement condition, the inconsistent information of visual and vestibular systems cause cybersickness. This can be explained by the sensory conflict theory. In contrast, there was no visual-vestibular conflict in the without scene movement condition. According to the cue-conflict theory, there should be little or no motion sickness in this condition.

7.7.1.2 Duration effect on nausea ratings

Result of ANOVA indicated that the duration has a significant main effect on nausea ratings in the 'with' scene movement condition (F(4,255)=50.28, p=0.0001, see Appendix F: Table F.3). Post-hoc SNK test showed that the effect of exposure duration was significant after 5 minutes (see Appendix: F: Table F.4), although the increase was not significant after 15 minutes of the simulation.

Also, result of ANOVA indicated that the duration has a significant main effect on nausea ratings in the 'without' scene movement condition ($F(4,75)=3.67$, $p=0.0087$, see Appendix F: Table F.5). Post-hoc SNK test showed that the effect of exposure duration was significant after 10 minutes (see Appendix F: Table F.6), although the increase was not significant after 15 minutes of the simulation.

Although, duration anticipated significant effect on nausea rating in the 'without' scene movement condition, the mean nausea ratings after 20 minutes was 0.4375. Furthermore by comparing the duration effect on nausea ratings between the 'with' and 'without' scene movement conditions, the results of ANOVA showed that, at each five minutes intervals (except at the beginning of the simulation) the nausea ratings in the 'with' scene movement condition were significantly higher than that of the 'without' scene condition (see Appendix F: Table F.7 & Table F.8). This suggests that the increase in nausea ratings in a dynamic virtual environment simulation is significant higher than that in a stationary virtual environment.

The means of nausea ratings with standard deviation of the four different conditions are shown in Figure 7.5.

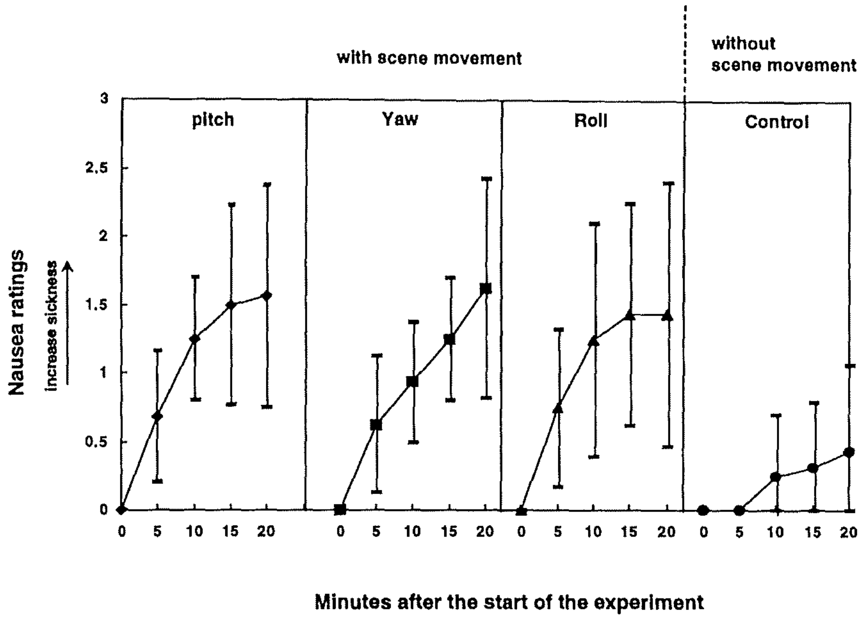


Figure 7.5. Nausea ratings after the start of the Experiment one (4 conditions)

7.7.1.3 Comparing the sickness symptoms and profiles between with and without scene movement conditions

Kennedy *et al.* (1993a) developed a procedure to score the 'symptom checklist questionnaire'. Sixteen items out of 28 were used in the calculation. The 16 items were marked with * in Appendix B. These 16 items were divided into three sub-scales — Nausea, Oculomotor and Disorientation. In addition, there was a Total Severity measure (Total sickness score). According to the scoring method, Nausea sub-scale includes symptoms such as general discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness and burping. Scores on the Oculomotor sub-scale are related to the symptoms such as general discomfort, fatigue, headache, eyestrain, difficulty focusing, difficulty concentrating and blurred vision. Score on the Disorientation sub-scale are related to symptoms such as difficulty focusing, nausea, fullness of head, blurred vision, dizziness and vertigo. Variable score (0:None, 1:slight, 2:Moderate, 3:Severe; or 0:No, 1:Yes) is assigned for each symptom. The score is multiplied by a weight (the value of each weight can be 0 or 1 as shown in Appendix E). The weighted total is obtained by summing the weighted values down the sub-scale column. The scores of nausea, Oculomotor and Disorientation are then obtained by multiplying the weighted totals (values just calculated in the previous step) with appropriate scaling factors. Finally, the Total Severity (Total sickness score) is obtained by summing all the totals and then applies the weight multiplier to the sum. The scoring method is shown in Appendix E.

The numbers of subjects who reported any symptom before and after the experiment (4 conditions) are shown in the following figures. Figure 7.6a presents the Nausea sub-scale, Figure 7.7b illustrates the Oculomotor sub-scale and the Disorientation sub-scale is shown in Figure 7.6c. Figure 7.6d points out the 12 symptoms of the symptom checklist questionnaire that are not classified in the three sub-scales.

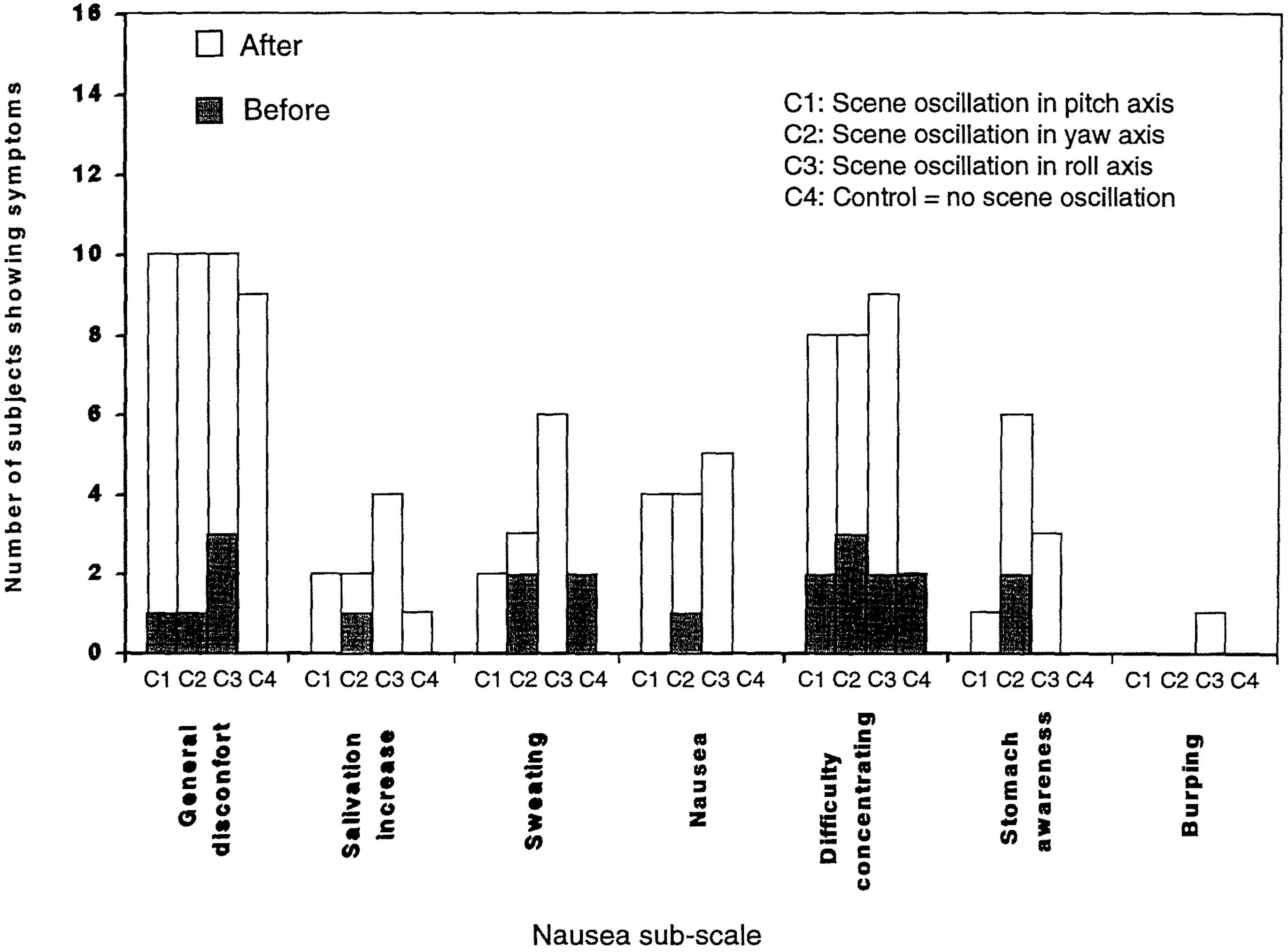


Figure 7.6a Number of subjects showing sickness symptoms (Nausea sub-scale) before and after the Experiment one (4 conditions).

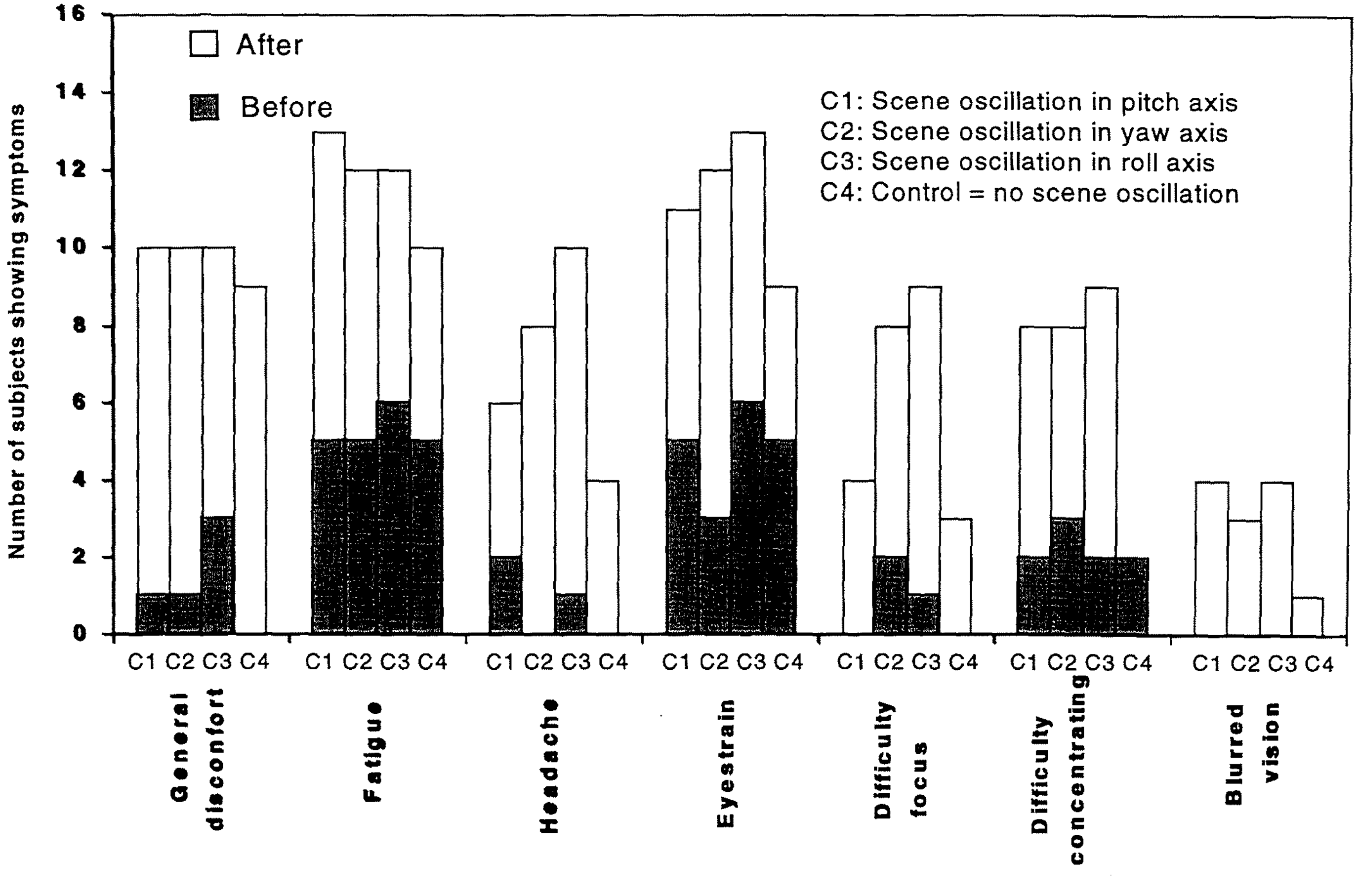


Figure 7.6b Number of subjects showing sickness symptoms (Oculomotor sub-scale) before and after the Experiment one (4 conditions).

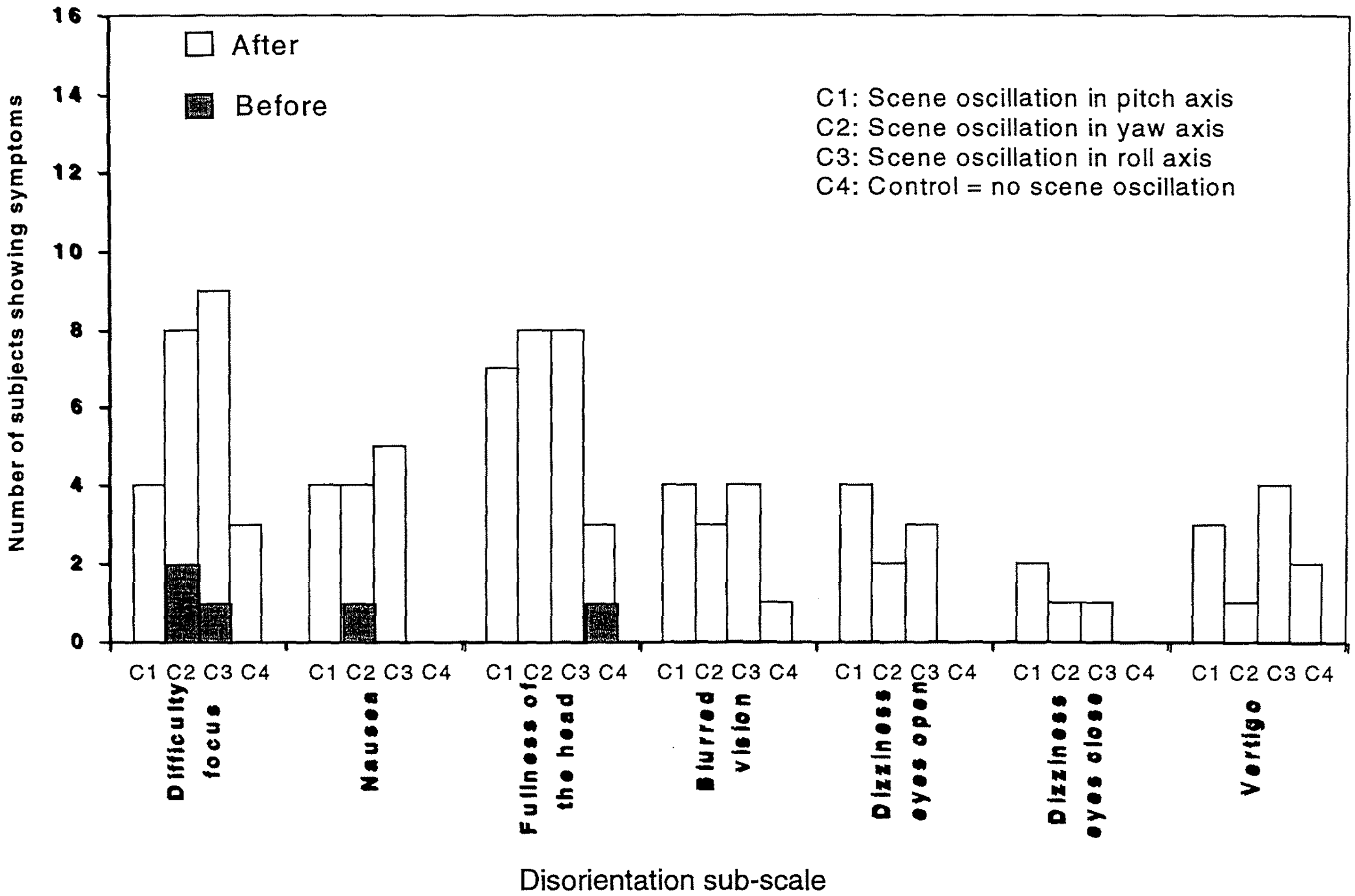


Figure 7.6c Number of subjects showing sickness symptoms (Disorientation sub-scale) before and after the Experiment one (4 conditions).

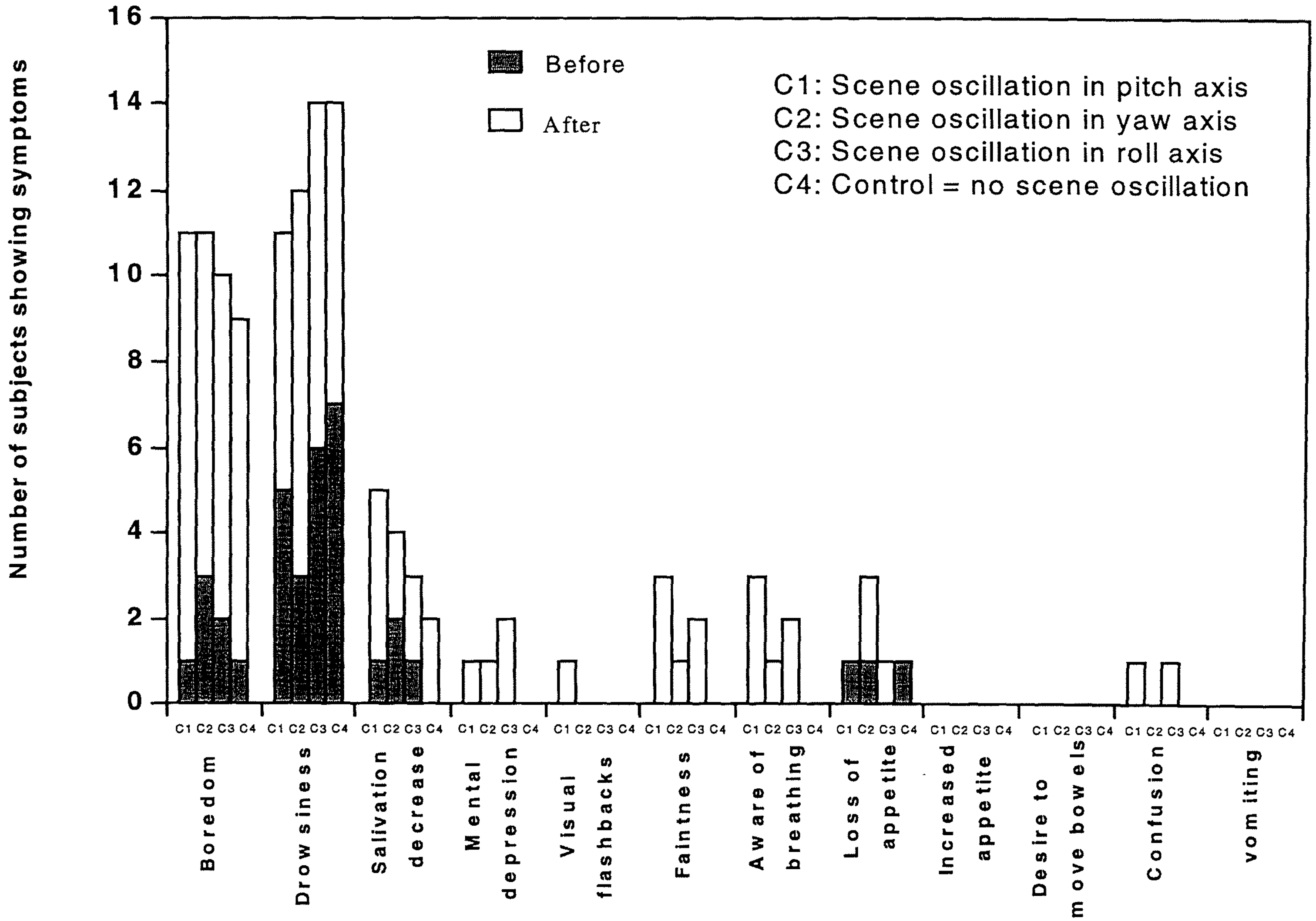


Figure 7.6d Number of subjects showing the other 12 symptoms (not classified in the three sub-scales) before and after the Experiment one (4 conditions).

Figures 7.6a and 7.6b describe that 10 subjects, in pitch, yaw and roll scene oscillation conditions, suffered signs of 'general discomfort' after the experiment while in control conditions, the number is 9. Comparing the 'general discomfort' with other symptoms in Nausea sub-scale, it was the mostly reported symptom (more subjects suffered from it after the experiment). Besides, 'difficulty concentrating' was the second most frequently reported symptom. Figure 7.6b illustrates that the numbers of subjects reporting each symptom on the Oculomotor sub-scale after the experiment were general higher than the other two sub-scales (Nausea and Disorientation). By comparing the number of subjects suffering form symptoms, the most frequently reported symptoms were 'eye strain' and 'fatigue'. More than 8 subjects suffered from 'eye strain' and more than 9 subjects suffered from 'fatigue' in all conditions. For example, with condition of scene oscillation in roll axis, 5 subjects reported slight 'eye strain' and 8 reported moderate 'eye strain' after the experiment. Eye stain is a very common reported symptom in simulator sickness (Kennedy *et al.*, 1990, 1994). Since the images presented on the head mounted display were focused at about 2 feet in this experiment, the consequence might be fatigue of eyes muscles and nervous. 'Fullness of head' and 'difficulty focusing' were the common reported symptoms of Disorientation sub-scale. Figure 7.6d illustrates that 'boredom' and 'drowsiness' were also frequently reported.

By comparing the 27 sickness symptoms between with and without scene movement conditions, nearly all symptoms except 'drowsiness' were less frequently reported (fewer subjects suffered from) in the 'without' scene movement condition. This suggests that exposure in a stationary virtual environment through a head-mounted display would cause fewer symptoms compared to a dynamic virtual environment simulation.

Figure 7.7 illustrates the pre-immersion, post-immersion and change sickness profiles for all conditions in the experiment (4 conditions). These profiles can be used to compare the side effect produced with other virtual reality or simulator systems using the same symptom checklist scoring method. The descriptive statistics is shown in Appendix F: Table F.9.

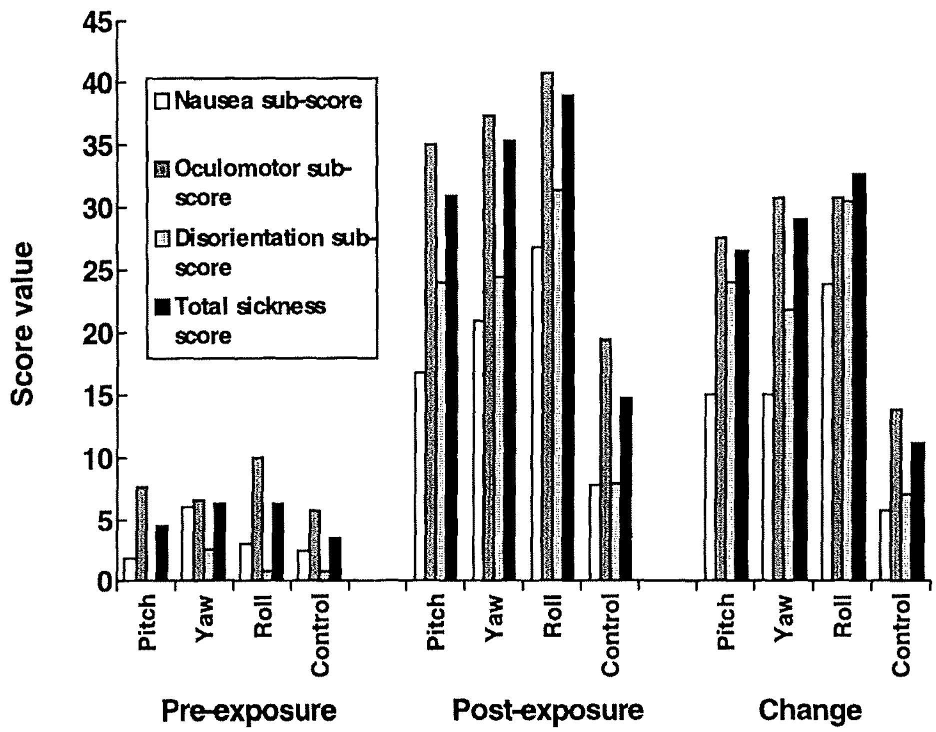


Figure 7.7 Illustration of the pre-immersion, post-immersion and change sickness profiles the four conditions of Experiment one individually

By investigating the pre-immersion sickness profiles, the results of ANOVA indicated that there were no significant differences in Nausea (N), Oculomotor (O), Disorientation (D) sub-scores and Total Sickness score (TS) among the 4 conditions (N: $F(3,60)=1.49$, $p=0.2263$; O: $F(3,60)=0.46$, $p=0.7134$; D: $F(3,60)=1.36$, $p=0.2625$; T: $F(3,60)=0.66$, $p=0.5789$; see Appendix F: Table F.10, F.11, F.12 & F.13 respectively). These results indicated that, subjects in different conditions were equally healthy before participated the experiment.

By comparing the post-immersion with pre-immersion sickness profiles of each condition individually, the results of ANOVA showed that there were significant differences in Nausea (N), Oculomotor (O), Disorientation (D) sub-scales and Total sickness score (TS) (see Appendix F: Table F.14, F.15, F.16 & F.17 respectively).

Figure 7.7 points out that, the sickness profiles for the 4 conditions are similar. The scores of Oculomotor (O) were highest, Disorientation (D) were medium while that of Nausea (N) were the lowest (i.e. O>D>N). The change profile of sickness score of without scene movement (control condition) was lower than that of the other three conditions.

By investigating the change of sickness profiles (difference of post and pre-immersion sickness profiles), the mean total sickness score of control condition (without scene movement) was 10.753, this values was smaller than those of the other three conditions (scene movement in pitch: 26.414, scene movement in yaw: 26.881, scene movement in roll: 32.725). The results of ANOVA showed that the difference between with and without scene movement conditions were significant in sickness score of Nausea sub-scale ($F(1,62)=7$, $p=0.0103$), Oculomotor ($F(1,62)=7.74$, $p=0.0072$), Disorientation ($F(1,62)=6.93$, $p=0.0107$) and the total sickness score TS ($F(1,62)=8.83$, $p=0.0042$, see Appendix F: Table F.18). Post-hoc SNK test proved that, simulation with scene movement would introduce significantly higher sickness score in Nausea (N), Oculomotor (O), Disorientation (D) and hence higher Total Sickness score (TS) to the subjects compare with simulation without scene movement (see Appendix F: Table F.19).

Figure 7.6a, 7.6b and 7.6c describe the individual symptoms of the three sub-scales while Figure 7.7 displays the average score (mean value of the 16 subjects) of the three sub-scales. Inspecting the results of these two graphs, the Oculomotor sub-score was noted to be the highest, which was mainly due to eyestrain and fatigue. Comparing the sickness profiles of this experiment with other reported profiles of flight simulator (with CRT display), similar profiles were presented (Kennedy *et al.*, 1994). On the other hand, it points out reverse of symptom profiles with other VE system. Other virtual reality systems generally have proportionately more Nausea and Disorientation and less Oculomotor problem (N>D>O) (Kennedy *et al.*, (1997); Regan (1993)). This contradiction may be due to fatigue and eyestrain, because subjects had to concentrate on the task. Furthermore, since the virtual image was focus at 2 feet in front of the display, user may suffer from eyestrain.

7.7.2 Result of Sickness ratings and symptoms among scene oscillation in pitch, yaw and roll axes

7.7.2.1 Effect of scene movement in different oscillation axes on nausea ratings

As mentioned before, the nausea ratings were significantly different between with and without scene movement. But within the scene movement condition, there were no significant differences among the three scene oscillations in the three different rotational axes ($F(2,225)=0.75$, $p=0.4733$, see Appendix F: Table F.20). It meant that, scene oscillation in pitch, or in yaw, or in roll would produce about the same level of nausea ratings.

7.7.2.2 Duration effect on nausea ratings

During the 20 minutes of the simulation, the nausea ratings increased with duration and become significant after five minutes with conditions of scene oscillation in pitch ($F(4,75)=21.25$, $p=0.0001$), yaw ($F(4,75)=23.68$, $p=0.0001$)

and roll ($F(4,75)=11.32$, $p=0.0001$) axes (see Appendix F: Table F.21 & F.22). The highest values of nausea ratings (mean of the 16 subjects) were recorded at 20 minutes for scene oscillation in all three axes. At 20 minutes, there was no significant difference among the nausea ratings with pitch, yaw, and roll oscillations ($F(2,45)=0.2$, $p=0.82$, see Appendix F: Table F.23).

7.7.2.3 Comparing the sickness symptoms and profiles among scene oscillation in pitch, yaw and roll axes

As mentioned before, the dominant symptoms of each condition in each sub-scale (Nausea, Oculomotor and Disorientation) were about the same. Besides, all conditions had the similar sickness profiles. In Nausea sub-scale, the dominant symptoms were 'general discomfort' and 'difficulty concentration'. 'Eye strain' and 'Fatigue' were the dominant symptoms in Oculomotor sub-scale, while the dominant symptoms of Disorientation sub-scale were 'difficulty focusing' and 'fullness of head'. Inspection of Figure 7.7 demonstrates that scene oscillation in roll axis condition resulted in the largest increase in sickness scores. Result of ANOVA indicated that there were no significant differences in Nausea sub-score ($F(2,45)=1.06$, $p=0.3565$), Oculomotor sub-score ($F(2,45)=0.11$, $p=0.8927$), Disorientation sub-score ($F(2,45)=0.41$, $p=0.6671$), Total sickness score ($F(2,45)=0.35$, $p=0.7092$, see Appendix F: Table F.24).

In addition, 2 subjects in roll scene oscillation condition, and 2 subjects in control condition reported that they suffered slight 'neck strain' after the experiment. Since throughout the whole experiment, subjects were asked to keep their head stationary, this might lead to neck muscle fatigue due to the weight of the head mounted display (0.935g).

7.7.3 The motion sickness history questionnaire results

The ten questions on motion sickness history questionnaire were scored (Appendix A). Question one, asked how many times the subjects traveled as a passenger in different type of transport, while questions two and three asked how many times the subjects felt ill or vomited in the types of transport mentioned in question one. In order to get a meaningful result we divided the result of question two by question one, and question three by question one. For question one to question three, numerical number 0 was assigned to 'Never', 1 to '1', 257 for the option '257 or more', while the other options, the average number of the interval of the option were assigned to it. For example, if the option is '65-256' then the numerical number 161 were assigned to it. After the above calculation, the result of questions two and three were represented as percentages. Numerical values were assigned to represent these percentages, 0 for Never, 1 for (>0% to 20%), 2 for (>20% to 40%), and so on. So the lowest value was zero and the highest value was 5 for each kind of transport in question two and question three. For question four, numeric value 1 was assigned to 'Yes' option and 0 to 'No'. In question five, numerical values 1 to 4 were assigned to 'Never' to 'Always' respectively. The option 'Much less than average' to 'Much more than average' in question six were represented by numerical values form 1 to 5. For question seven to question ten, the assignment of numerical values to options was — 0: 'Never', 1: '1', 2: '2-4', 3: '5-16', 4: '17-64', 5: '65-256', 6: '257 or more'.

In the calculation of motion sickness susceptibility, only question six and question seven were used. It is because, question six asked the subject's susceptibility to motion sickness while question seven asked the subject how many times have they suffered travel sickness (sea, air and land transport) in their life. Regan (1995) used four questions to determine the motion sickness susceptibility of the subjects. The four question are: (i) How often would you say you get airsick, (ii) How often would you say you get seasick, (iii) How often would you say you get carsick and (iv) How susceptibility to motion sickness do you feel you are. Which are just similar the questions six and seven in this study.

Since only question six and seven were directly related to motion sickness susceptibility, only these two questions were used to determine the subject's susceptibility to motion sickness. Since the minimum score in question 6a, 6b were both 1 but 0 in question 7, while the highest score in question 6a and 6b were 5, but 6 in question 7. Therefore, the minimum score for the motion sickness susceptibility was 2 and maximum score was 16. According to the subjects' score on these two questions subjects were classified as having low motion sickness susceptibility if they scored between 2 to 4, moderate motion sickness susceptibility if they scored between 5 to 10, or high motion sickness susceptibility if they scored between 11 to 16.

According to the above method, the result showed that there was 1 subject (6.25%) being classified as having low motion sickness susceptibility, 13 (81.25%) in the class of moderate motion sickness susceptibility, and 2 (12.5%) in the class of high motion sickness susceptibility.

Correlation was carried out on the motion sickness history questionnaire. The result showed that there were no significant correlation between the nausea rating at 20 minutes (highest nausea rating) and motion sickness susceptibility. In addition, computer or video game experience, fair ground simulators experience and fill ill or got sick in transport experience were in general not correlated with motion sickness susceptibility and highest nausea rating.

7.7.4 The simulation assessment result

The results of ANOVA indicated that there were no significant differences in the answers to question 2 (Q2), question 3 (Q3), question 4 (Q4), question 5 (Q5) and question 6 (Q6) among the 4 conditions. Table 7.1 summarizes the ANOVA results (for details see Appendix F: Table F.25).

Table 7.1 ANOVA results for answers to question 1 to 6 of simulation assessment questionnaire

(Note that * indicated a significant effect at $p<0.05$ level)

Item (Question)	ANOVA Result
Question 1 (Q1) During the simulation, did you feel that you were moving? (Perception of vection)	$F(3,60) = 20.99$, $p=0.0001$*
Question 2 (Q2) How uncomfortable was the head-mounted display (HMD)? (Uncomforted of HMD)	$F(3,60) = 1.76$, $p=0.1652$
Question 3 (Q3) How completely did you believe you were part of the virtual environment? (Sense of presence)	$F(3,60) = 0.561$, $p=0.6781$
Question 4 (Q4) How flat and missing in depth did the world appear? (Flat & missing of VE)	$F(3,60) = 0.38$, $p=0.7696$
Question 5 (Q5) How excited do you feel after the experience? (Excitement)	$F(3,60) = 1.29$, $p=0.2865$
Question 6 (Q6) How real was the graphics simulation? (Realism of simulation)	$F(3,60) = 0.60$, $p=0.6171$)

Inspection of Table 7.1 shows that, the answer to question 1 (Q1: perception of vection) were significantly different among the four conditions. It was because in control condition, the scene was stationary through the 20 minutes simulation. Therefore subjects participating under this condition would not perceive apparent self-motion.

Pearson correlation tests were performed among the answer to items (Q1-Q6) of Table 7.1 and nausea rating at 20 minutes of the simulation (see Table 7.2) Although the correlation coefficients were not very high, some items showed that the p values were less than 0.05. 'Believe part of virtual environment' correlated with ' Apparent self-motion' (r=0.28591, p=0.022). It means that the sense of presence increase, the feeling of apparent of self-motion would also increase. 'Believe part of virtual environment' correlated with 'flat and missing in depth of the virtual environment', 'excitement' and 'Realism of the simulation. While ' Realism of the simulation were also correlated with 'Flat and missing in depth of virtual environment' and 'excitement'. Besides, 'apparent self-motion' shows correlation with nausea rating after 20 minutes of the simulation (r= 0.41958, p=0.00061).

Table 7.2 Inter-correlation coefficients for answers to question 1 to 6 of the simulation assessment form and nausea rating after a 20 minutes VR simulation

	Q1	Q2	Q3	Q4	Q5	Q6	Nausea rating at 20 minutes
Q1	1	-0.01694	0.28591	0.21375	0.36008	0.21948	0.41958
	0	0.8943	0.022	0.0899	0.0035	0.0814	0.0006
Q2	-0.01694	1	-0.06237	0.19876	-0.14509	-0.01196	0.2982
	0.8943	0	0.6244	0.1154	0.2527	0.9253	0.0167
Q3	0.28591	-0.06237	1	0.31614	0.39161	0.48621	0.13213
	0.022	0.6244	0	0.0109	0.0014	0.0001	0.298
Q4	0.21375	0.19876	0.31614	1	0.07472	0.31011	0.20259
	0.0899	0.1154	0.0109	0	0.5574	0.0126	0.1084
Q5	0.36008	-0.14509	0.39161	0.07472	1	0.4447	-0.00077
	0.0035	0.2527	0.0014	0.5574	0	0.0002	0.9952
Q6	0.21948	-0.01196	0.48621	0.31011	0.4447	1	0.03016
	0.0814	0.9253	0.0001	0.0126	0.0002	0	0.813
Nausea rating after 20 minutes	0.41958	0.2982	0.13213	0.20259	-0.00077	0.03016	1
	0.0006	0.0167	0.298	0.1084	0.9952	0.813	0

7.8 Summary

In conclusion, over the 20 minutes immersive VR simulation presented via a head-mounted display, nausea ratings increased significantly with time. Besides, the presence of scene movement significantly increased the levels of cybersickness. The results indicated that a stationary scene of VR simulation might cause less sickness than a dynamic VR simulation. In addition, there were no significant differences among the nausea ratings obtained with scene oscillations in three different rotational axes — pitch, yaw and roll. This did not agree with the hypothesis that pitch axis oscillation should result in higher levels of cybersickness. A possible reason is that the hypothesis was based on literature concerning real physical motion rather than virtual scene oscillation. With actual physical head movements, due to gravitation force, the head pitch movement (along the gravitational force vector) would produce a stronger stimulus to the vestibular system. Since the yaw head movement is perpendicular to the gravitational force, it would produce weaker stimulus to the vestibular system. Therefore, many past studies reported that pitch head movement would produce stronger levels of motion sickness (Griffin, 1991; Benson and Guedy, 1971). The result of Experiment one showed that pitch vection produced about the same level of cybersickness as compared with yaw vection and roll vection. In Experiment one, subjects did not have body or head movements, so no matter how the scene oscillated in the simulation, the same signal (constant gravitational force) was received by the vestibular system. As the scene oscillations in the three axes had the same magnitude and frequency, the level of visual-vestibular conflict were about the same in the pitch, yaw and roll vection conditions. According to the sensory conflict theory, similar conflict would produce similar levels of vection-induced motion sickness.

The result of motion sickness questionnaire suggested that there was no evidence for relationship between levels of reported cybersickness (nausea) ratings and their self-rated susceptibility to motion sickness.

Analysis of pre-immersion and post-immersion symptom checklist suggested that the VR system with head-mounted display would cause high Oculomotor problems (due to eye-strain) in this experiment. Also, there were no significant differences among the sickness profiles (Nausea sub-score, Oculomotor sub-score, Disorientation sub-score and Total Sickness score) among scene oscillations in pitch, yaw, and roll axes.

All in all, the result of this experiment has confirmed that visual scene movement plays an important role in generating cybersickness.

Chapter 8 Studies of effects of scene velocity on cybersickness with a head-coupled virtual reality system (Experiment two)

8.1 Purpose of this experiment

Scene velocity is one of the two main components of the proposed 'spatial velocity' metric for quantifying scene movement. It is important to conduct an experiment to confirm that scene velocity will influence the level of cybersickness.

8.2 Objective and hypothesis

An experiment was conducted to study the effects of scene velocity on cybersickness. The specific objective was to determine the relationship between scene velocity and the rated level of cybersickness. It is hypothesized that the higher the visual scene velocity the higher the rated level of cybersickness.

8.3 Dependent and independent variables

In this study, two independent variables were used: (i) duration of exposure to virtual reality simulation (0 to 30 minutes), (ii) scene velocity (5 different levels). Table 8.1 summarizes the spatial frequencies, scene velocities and spatial velocities of the five conditions. Since the virtual environment of the 5 conditions were the same ,the spatial frequencies were the same for the 5 different conditions (Five representative snapshots of the virtual environment are illustrated in Figure 4.3 of Chapter 4). The time history curves of scene displacements and scene velocities of the 5 conditions are shown in Appendix L, M, N, O and p respectively.

Table 8.1 Spatial frequencies, scene velocities and spatial velocities of the five scene velocity conditions

			Level of scene velocity				
			1	2	3	4	5
r.m.s scene velocity [v]	Translational (m/s)	X-axis	3.4331	4.3636	6.0001	9.5944	23.9864
		Y-axis	1.0743	1.4118	1.9367	3.1137	7.7843
		Z-axis	0.222	0.2586	0.3626	0.5919	1.4789
	Rotational (deg/s)	Roll	0.4984	0.5851	0.8241	1.4143	3.5357
		Pitch	0.5634	0.7785	1.0541	1.6331	4.0827
		Yaw	3.7916	4.9556	6.8278	10.9898	27.4745
Spatial frequency [SF]	Horizontal (cyc/deg)		0.1556				
	Vertical (cyc/deg)		0.1338				
	Radial (cyc/deg)		0.2086				
Spatial Velocity [SV]	Translational (cyc·m/s·deg)	X-axis	0.7161	0.9102	1.2516	2.0014	5.0036
		Y-axis	0.1671	0.2196	0.3013	0.4844	1.2109
		Z-axis	0.0297	0.0346	0.0485	0.0792	0.1979
	Rotational (cyc/s)	Roll	0.1040	0.1221	0.1719	0.2950	0.7375
		Pitch	0.0754	0.1042	0.1411	0.2186	0.5464
		Yaw	0.5898	0.7709	1.0621	1.7096	4.2739
Average translational scene velocity (m/s) [X-axis+Y-axis+Z-axis]			1.5765	2.0113	2.7665	4.4333	11.0832
Average rotational scene velocity (deg/s) [Pitch+Yaw+Roll]			1.6178	2.1064	2.902	4.6791	11.6976
Average translational spatial velocity (cyc·m/s·deg) [X-axis+Y-axis+Z-axis]			0.3043	0.3882	0.5338	0.8550	2.1375
Average rotational spatial velocity (cyc/s) [Pitch+Yaw+Roll]			0.2564	0.3324	0.4584	0.7411	1.8526

During the virtual guided tour simulation, subjects would travel through a virtual city passively on a pre-determined close loop path. The motion of the path contains movement in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes.

The simulation took place in a darkened environment so that the only visual stimulus came from the VR4 head-mounted display. The laboratory was air-conditioned in order to eliminate the temperature and ventilation variables. The temperature of the room was kept at about 23°C and the relativity humidity was about 58%.

The dependent variables were: (i)the level of sickness rating, (ii) level of apparent self-motion (vection) ratings, (iii) sickness symptoms and (iv) rated realism of simulation. A motion sickness history questionnaire (Appendix K) was used to estimate subjects' susceptibility to motion sickness. The questionnaire was developed by R.H.Y. So and Colleen Finney and has been used in an internal course project in the IEEM department of HKUST (1997).

Before the simulation, subjects were asked to complete a symptom checklist containing 27 items (adapted from Kennedy *et al.*, 1993, see appendix B). After the simulation, subjects were required to fill out this checklist again to compare reported symptoms before and after simulation.

A seven point subjective rating scale (adapted from Golding and Kerguelen, 1992) was used to measure the level of unpleasant feeling during the simulation (see Appendix C). This scale ranged from 'no symptom' to 'moderate nausea' scale. A four point subjective rating scale (see Table 8.2) was used to measure the level of apparent self-motion illusion (vection) during the virtual simulation.

Table 8.2. The four point apparent self-motion rating scale

Apparent self-motion ratings	Definitions
0	No
1	Slight
2	Moderate
3	Strong

After the 30 minutes experiment, the realism of the virtual environment was measured using a simulation assessment questionnaire (modified from Regan and Price, 1993a, see Appendix D).

8.4 Apparatus and virtual reality software

The simulation was developed using a virtual reality authoring software (dVISE) running on a Silicon Graphics ONYX2 workstation. The general arrangement of experimental apparatus is described in Chapter 7: Figure 7.3. A Polhemus 3-SPACE magnetic tracker was used to measure head position and orientation at 30 samples per second. This tracker was mounted on top of a head-mounted display (VR4: 48° horizontal 36° vertical).

Same visual scenes were presented to both eyes and the images completely overlaid each other (i.e. biocular images). The images were focused at around 2 feet in front of the display and were continuously updated according to head orientation at 30 frames per second. The weight of the head-mounted display was 0.935kg and the pixel resolution was 742 (horizontal) 230 (vertical).

8.5 Visual scene content of the simulation

During the 30 minutes simulation, the visual scene consisted of some buildings, several railways, power lines, a train station, trains, workers, some billboards, bridges, grasslands, traffic lights and a blue sky with some white clouds.

8.6 Method and Design

Sixty male Chinese volunteers participated in the experiment. They were staffs and students of the Hong Kong University of Science and Technology (age: 19 to 39). They were randomly assigned to one of the 5 conditions. Each condition has

12 subjects participating. Five levels of scene velocity were investigated in this experiment: The spatial frequencies, scene velocities and spatial velocities of the 5 conditions are summarized in Table 8.1. All experimental procedures were the same in the 5 conditions, except the scene velocity. During each condition, subjects would be exposed to a 30 minute virtual reality simulation. Before the subjects participated the experiment, they were asked to complete a colorblindness test and a motion sickness history questionnaire. All subjects received HK$50 to compensate for their time.

The 60 subjects were briefed about the experiment and were then asked to read and sign a consent form. They were informed that they could withdraw from the experiment at any time on request and under no obligation to give reasons for withdrawal or to attend again for experimentation. At the beginning of the experiment, subjects were asked to rest for five minutes to minimize any unwanted influence from previous activities. The subjects were then required to complete a 'sickness symptom checklist', adapted from Kennedy (1993, see Appendix B). The inter pupillary distance of the subjects was measured prior to their data sessions so that the distance between left and right display of the head-mounted display (HMD) could be adjusted accordingly. Subjects would then put on the HMD and one minute practice was given to the subjects to familiarize themselves with the equipment. During this one minute practice, subjects were allowed to move their heads to inspect the virtual environment that they were 'immersed' in. Subjects remained seated throughout the simulation.

The chair they sat had a back-rest, a lumber support and two arm-rests. Before the simulation, the height of the chair was adjusted according to the subjects' preference. In this study, the scene motions were controlled during the 30 minutes of the simulation. At 30 seconds intervals from the start of the simulation, subjects were asked verbally to turn their heads to the right (about 55°~65°) and then face straight again. Further 30 seconds they were verbally asked to turn their heads to the left (55°~65°) and then face straight again. These kind of discrete head movements were repeated over the whole 30 minutes simulation. At five-minute intervals from the start of the simulation, subjects were verbally asked to rate their symptoms of nausea on a seven-point nausea scale (Appendix C) and level of apparent self-motion (vection) on a four-point scale (Table 8.2). After the simulation session, the subject were asked to complete another 'sickness symptom checklist' and a 'simulation assessment questionnaire' (Appendix D).

8.7 Result and Discussion

8.7.1 Results of sickness ratings and symptoms in five different levels of scene velocity

8.7.1.1 Effects of scene velocity and duration on nausea ratings

A two factors (scene velocity * duration) ANOVA was performed for the dependent variable of nausea ratings (see Appendix Q: Table Q.1). There was no significant interaction between the two factors ($F(24,385)=0.79$, $p=0.7515$). The five different scene velocities were significantly different in nausea ratings. A post-hoc Student Newman Keuls (SNK) test showed that scene velocity level 4(average translational velocity = 4.4333, average rotational velocity =4.6791) and scene velocity level 5(average translational velocity =11.0832, average rotational velocity = 11.6976) were not significantly different from each other but significantly different form the scene velocity level 3 (average translational velocity = 2.7665, average rotational velocity =2.902), scene velocity level 2(average translational velocity = 2.0113, average rotational velocity = 2.1064) and scene velocity level 1(average translational velocity = 1.5765, average rotational velocity = 1.6178). In addition, the SNK test also illustrated that scene velocity level 3, level 2 and level 1 were not significantly different from each other (see Appendix Q: Table Q.2). Nine subjects withdrew from the experiment before the end of the experiment because they suffered from 'moderate nausea' (6 on the scale of Appendix C). Five out of those nine subjects were participating in the scene velocity level 4, three in the scene velocity level 5 and 1 in the scene velocity level 3. This suggested that simulation with average translational velocity =11.0832 and average rotational velocity = 11.6976 was more nauseogenic than other conditions of this experiment. For the purpose of data analysis, after a subject withdrew from the experiment, a nausea rating of 6 was assigned until the end of the simulation. Besides, the values of apparent self-motion ratings of the time they withdrew were assigned until the end of the simulation.

Duration anticipated significant effect on nausea ratings ($F(6,385)=29.12$, $p=0.0001$) (see Appendix Q : Table Q.1). On the whole, the SNK test showed that nausea ratings were significantly different after 10 minutes (see Appendix Q: Table Q.3). Besides, by investigating the effect of duration on nausea ratings of each condition individually, the mean nausea ratings increased significantly with exposure duration in all conditions (see Appendix Q: Table Q.4a & Table Q.4b). Although the increases were not significant even after 25 minutes of simulation in all condition. The mean nausea ratings as function of exposure duration with stand derivation of the 5 conditions are shown in Figure 8.1

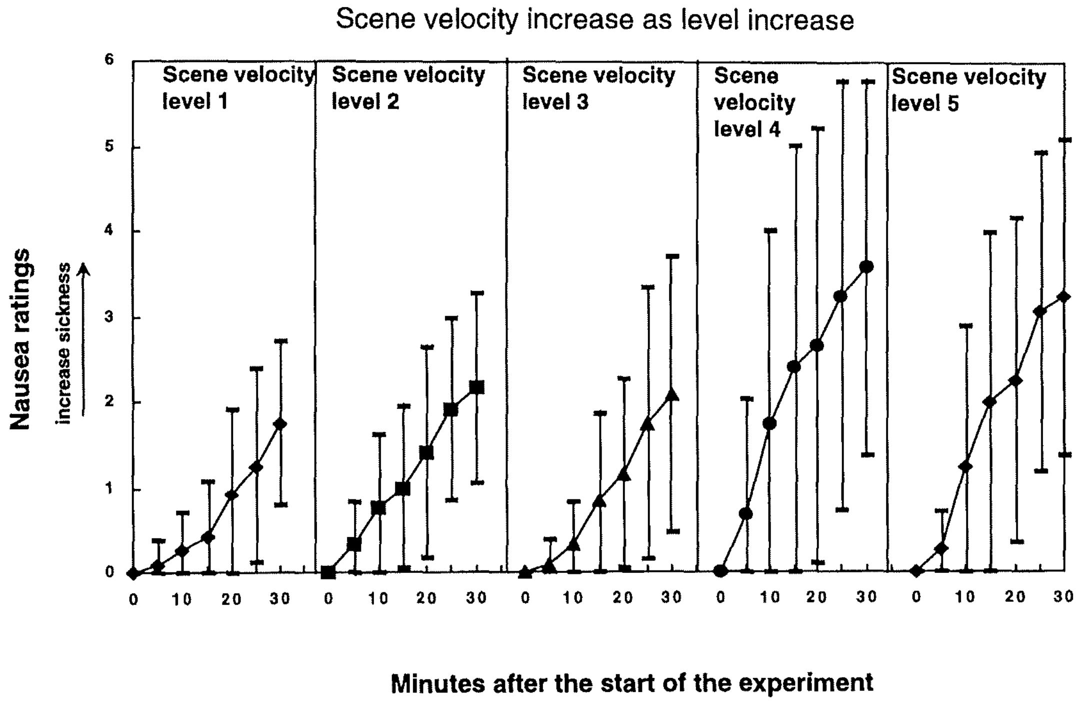


Figure 8.1 Mean nausea ratings as function of exposure duration with stand derivation of the 5 different scene velocity conditions

8.7.1.2 Effects of scene velocity and duration on apparent self-motion ratings

A two factors (scene velocity * duration) ANOVA was performed for the dependent variable of apparent self-motion ratings (see Appendix Q: Table Q.5). There was no significant interaction between the two factors ($F(24,385)=0.47$, $p=0.9862$). The five different scene velocities were significantly different in apparent self-motion ratings ($F(4,385)=5.13$, $p=0.0005$). A post-hoc Student Newman Keuls (SNK) test showed that scene velocity level 4(average translational velocity = 4.4333, average rotational velocity = 4.6791) and scene velocity level 5(average translational velocity =11.0832, average rotational velocity = 11.6976) were not significantly different from each other but significantly different form the scene velocity level 3 (average translational velocity = 2.7665, average rotational velocity = 2.902), scene velocity level 2(average translational velocity = 2.0113, average rotational velocity = 2.1064) and scene velocity level 1(average translational velocity = 1.5765, average rotational velocity = 1.6178). In addition, The SNK test also showed that scene velocity level 3, level 2 and level 1 were not significantly different from each other (see Appendix Q: Table Q.6).

Duration anticipated significant effect on apparent self-motion ratings ($F(6,385)=33.79$, $p=0.0001$) (see Appendix Q : Table Q.5). On the whole, the SNK test showed that apparent self-motion ratings were significantly different after 5 minutes (see Appendix Q: Table Q.7). Besides, by investigating the effect of duration on apparent self-motion ratings of each condition individually, the mean apparent self-motion ratings increased significantly with exposure duration in all conditions (see Appendix Q: Table 8a & Table 8b). However the increases were not significant even after 25 minutes of simulation in all condition. The mean apparent self-motion ratings as function of exposure duration with stand derivation of the 5 conditions are shown in Figure 8.2.

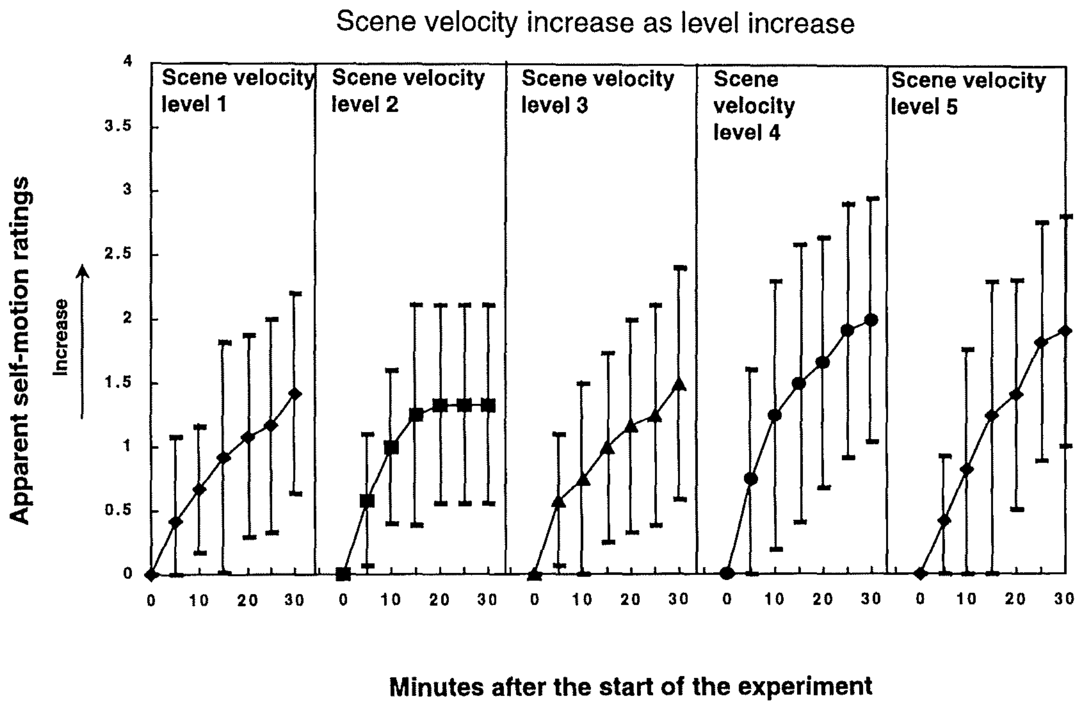


Figure 8.2. Mean apparent self-motion ratings as function of exposure duration with stand derivation of the 5 different scene velocity conditions

Scene velocity showed significant effect on nausea and apparent self-motion ratings, nausea ratings showed a strong correlation with apparent self-motion ratings ($r=0.81267$, $p=0.0001$). It indicated that the higher the perception of vection, the VR users would suffer higher rated level of nausea and vice versa. It confirmed the sensory conflict theory.

8.7.1.3 Comparing the sickness symptoms and profiles among the five different levels of scene velocity

The numbers of subjects who reported any symptom before and after the experiment (5 conditions) are shown in the following figures. Figure 8.3a presents the Nausea sub-scale, Figure 8.3b illustrates the Oculomotor sub-scale while the Disorientation sub-scale is described in Figure 8.3c. Figure 8.3d points out the 12 symptoms of the symptom checklist that are not classified in the three sub-scales.

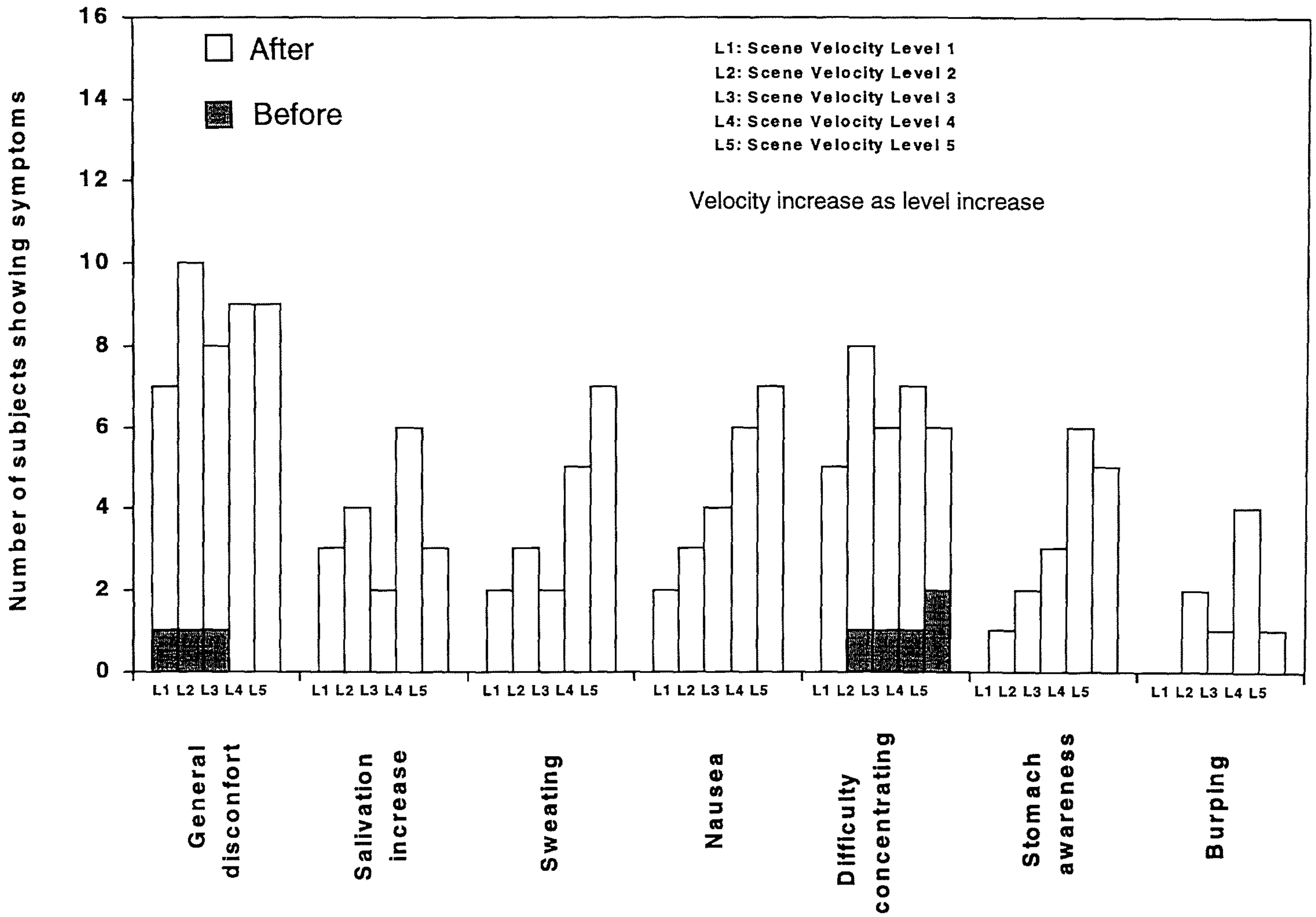


Figure 8.3a Number of subjects showing sickness symptoms (Nausea sub-scale) before and after the Experiment two

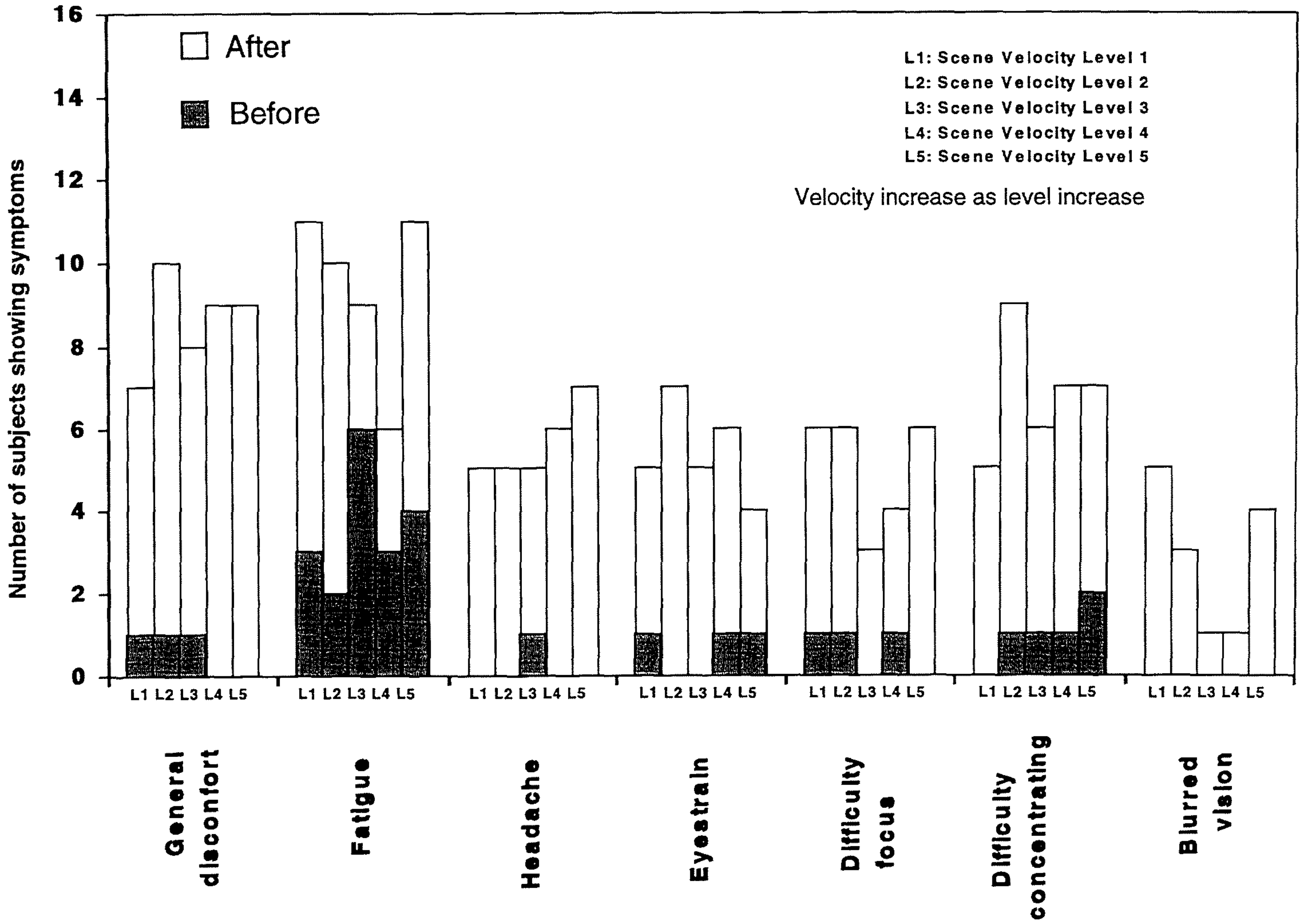


Figure 8.3b Number of subjects showing sickness symptoms (Oculomotor ub-scale) before and after the Experiment two

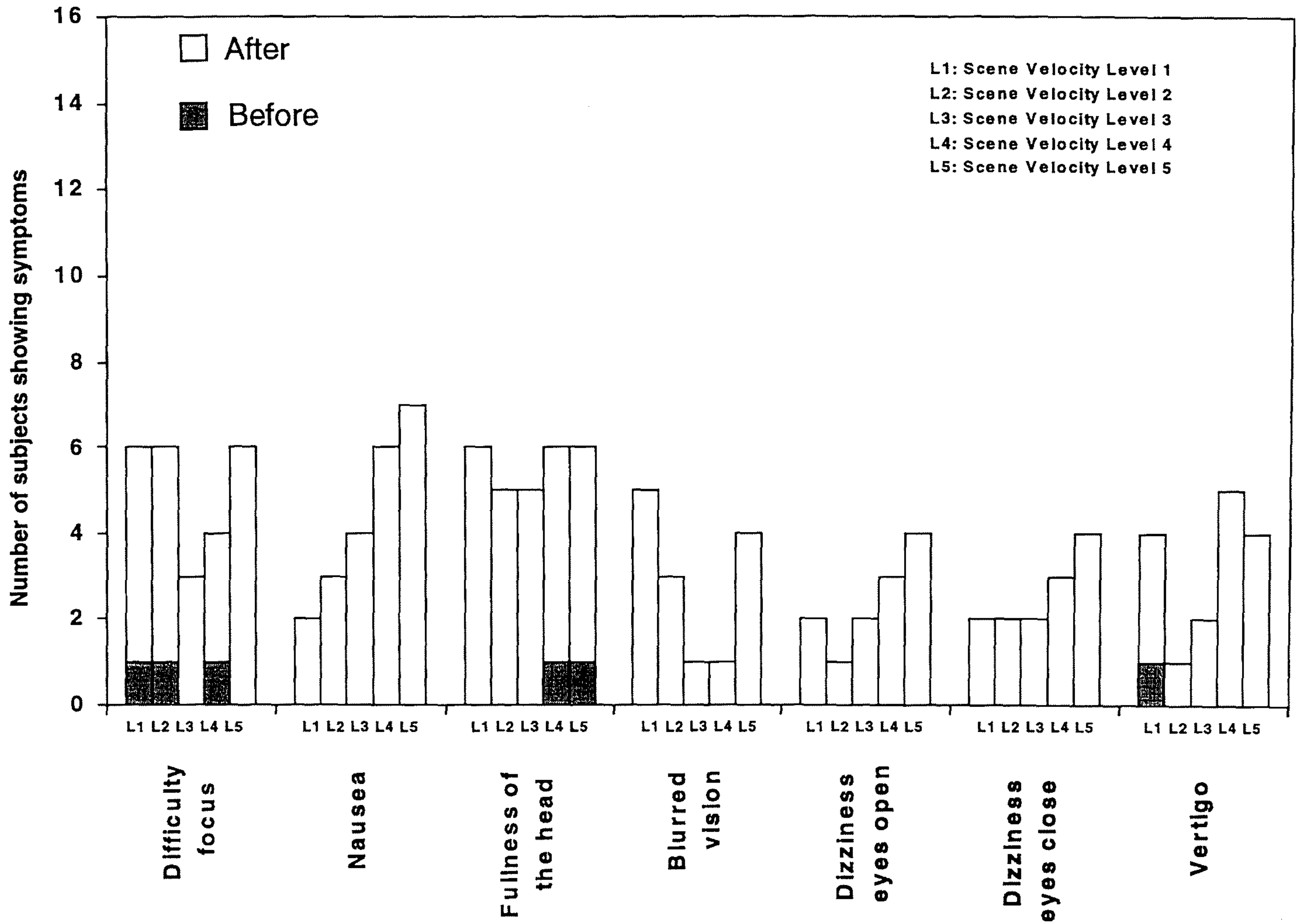


Figure 8.3c Number of subjects showing sickness symptoms (Disorientation sub-scale) before and after the Experiment two

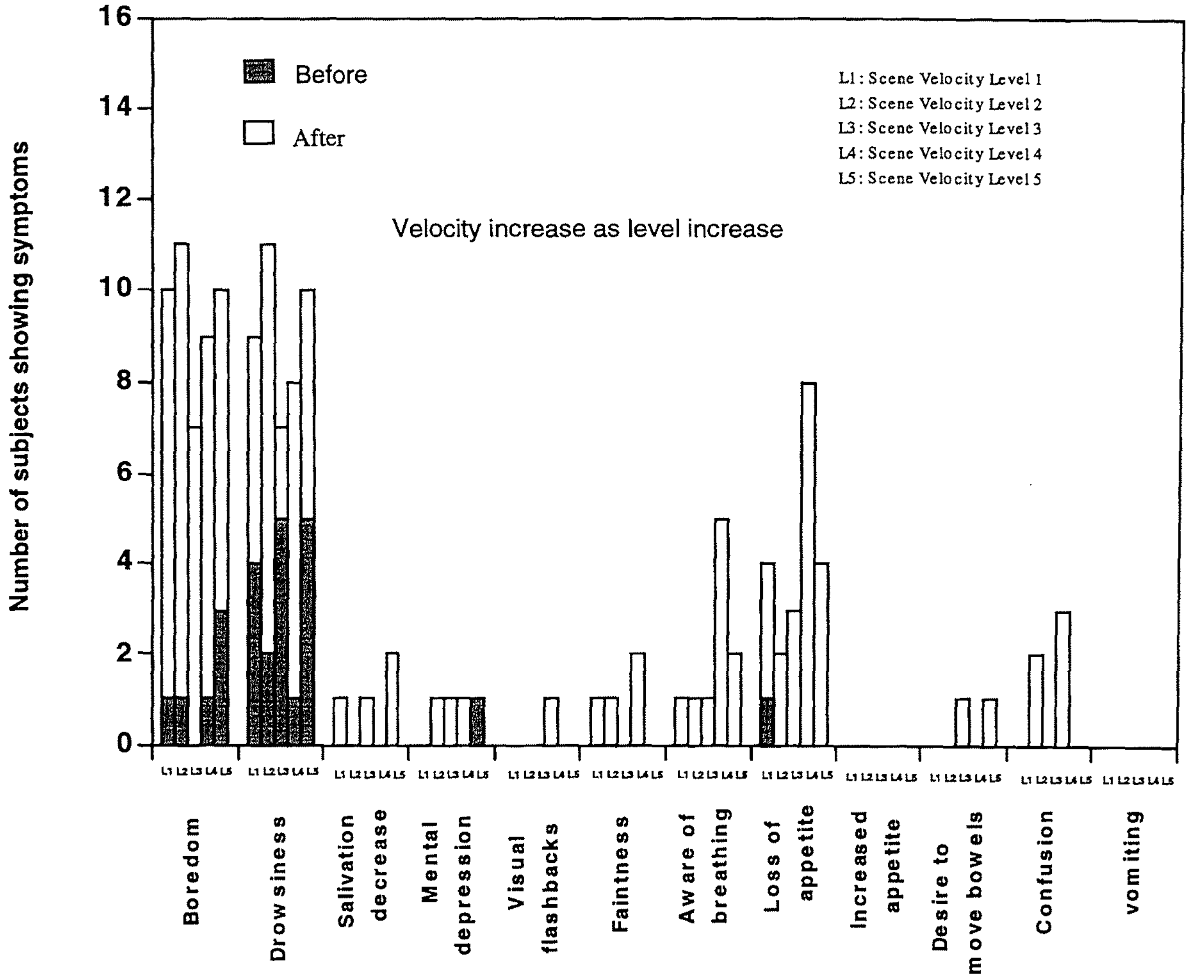


Figure 8.3d Number of subjects showing the other 12 symptoms (not classified in the three sub-scale) before and after the Experiment two

Comparing the 'general discomfort' with other symptoms in Nausea sub-scale (see Figure 8.3a), it was the mostly reported symptom (more subjects suffered from it after the experiment). Besides, 'difficulty concentrating' was the second most frequently reported. Figure 8.3b shows that 'general discomfort' and 'fatigue' were frequently reported in all conditions. Figure 8.3 c illustrates that 'difficulty focus' and 'fullness of the head' were frequently reported symptoms in the Disorientation sub-scale. Figure 8.3d describes that 'boredom' and 'drowsiness' were also frequently reported.

Figure 8.4 illustrates the pre-immersion, post-immersion and change sickness profiles (difference between pre and post) for all subjects in the experiment (5 conditions). The descriptive statistics is shown in Appendix Q: Table Q.9. By investigating the pre-immersion profile, there were no significant differences on Nausea sub-score (N), Oculomotor sub-score (O), Disorientation sub-score (D) and Total Sickness Score (TS) among the 5 different levels of scene velocity (N: $F(4,55)=0.16$, $p=0.9596$; O: $F(4,55)=0.24$, $p=0.9150$; D: $F(4,45)=0.62$, $p=0.6495$; TS: $F(4,45)=0.06$, $p=0.9937$, see Appendix Q: Table Q.10, Q.11, Q.12, Q.13 respectively). This result indicated that, subjects in different conditions were equally healthy before participating in the experiment. By comparing the post-immersion with pre-immersion sickness profiles of each condition, the sub-score of Nausea (N), Oculomotor (O), Disorientation (D) and Total Sickness score (TS) were significantly different (see Appendix Q: Table Q.14, Q.15, Q.16 & Q.17).

The result showed that after the 30 minutes virtual guided tour simulation, the subjects felt uncomfortable.

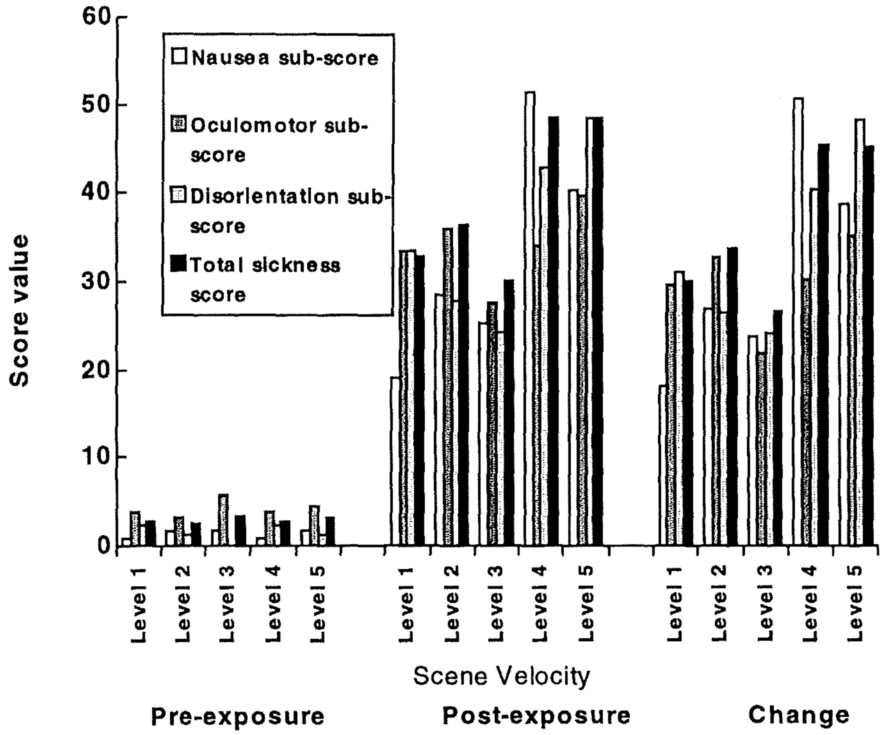


Figure 8.4 Illustration of the pre-immersion, post-immersion and change sickness profiles of the five different scene velocity levels individually

The sickness profiles were distinguishable between the 5 conditions. Table 8.3 summarizes the ranking of the three sub-scores of each condition.

Table 8.3 Ranking of Nausea, Oculomotor and Disorientation sub-scores for the 5 different scene velocity conditions

Scene velocity	Ranking of Nausea (N), Oculomotor (O) and Disorientation (D) sub-scores
Level 1	D (mean: 31.3200) > O (mean: 29.6883) > N (mean: 18.2850)
Level 2	O (mean: 32.8467) > N (mean: 27.0300) > D (mean: 26.6800)
Level 3	D (mean: 24.3600) > N (mean: 23.8500) > O (mean: 22.1080)
Level 4	N (mean: 50.8800) > D (mean: 40.6000) > O (mean: 35.3733)
Level 5	D (mean: 47.5600) > N (mean: 38.9550) > O (mean: 30.3200)

According to the table, the sickness profiles may be related to the scene velocity. Different scene velocities may give different sickness profiles. Scene velocity level 5(average translational velocity =11.0832, average rotational velocity = 11.6967) and scene velocity level 3 (average translational velocity = 2.7665, average rotational velocity = 2.902) showed similar sickness profiles (D>N>O), but the values of the three sub-scores in scene velocity level 5 were higher than those of scene velocity 3. Table 8.4 summarizes the ranking of Total Sickness score (TS) of the change profiles among the 5 different scene velocity conditions.

Table 8.4 Ranking of Total Sickness Score (TS) of the change profiles among the 5 different scene velocity conditions

Order	Scene velocity with the value of the Total Sickness Score (TS) in the change profiles
1st	Level 4 (TS = 45.8150)
2nd	Level 5 (TS = 45.5033)
3rd	Level 2 (TS = 33.9717
4th	Level 1 (TS = 30.2317)
5th	Level 3 (TS = 26.8033)

Further, The results of ANOVA reported that scene velocity did not show significant effect in Nausea (N), Oculomotor (O), Disorientation (O) sub-scores and the Total sickness score (TS) on the change sickness profiles (N: $F(4,55)=2.04$, $p=0.1021$; O: $F(4,55)=0.61$, $p=0.6600$; D: $F(4,55)=1.21$, $p=0.3191$; TS: $F(4,55)=1.1$, $p=0.3639$; see Appendix Q : Table Q.18, Q.19, Q.20, & Q.21).

8.7.2 The motion sickness history questionnaire results

Question 1 of the motion sickness history questionnaire (Appendix K), asked the percentage that the subjects having experienced motion sickness while travelling as a passenger in car/taxi, buses, cross-ferry, jet-foil, train (MTR/KCR) and elevators in the past 12 months. The number of subjects showing motion sickness while travelling as a passenger in these different types of transport are shown in Figure 8.5 while Table 8.5 illustrates the number of subjects showing the corresponding symptoms experienced while travelling as passenger in these different type of transports.

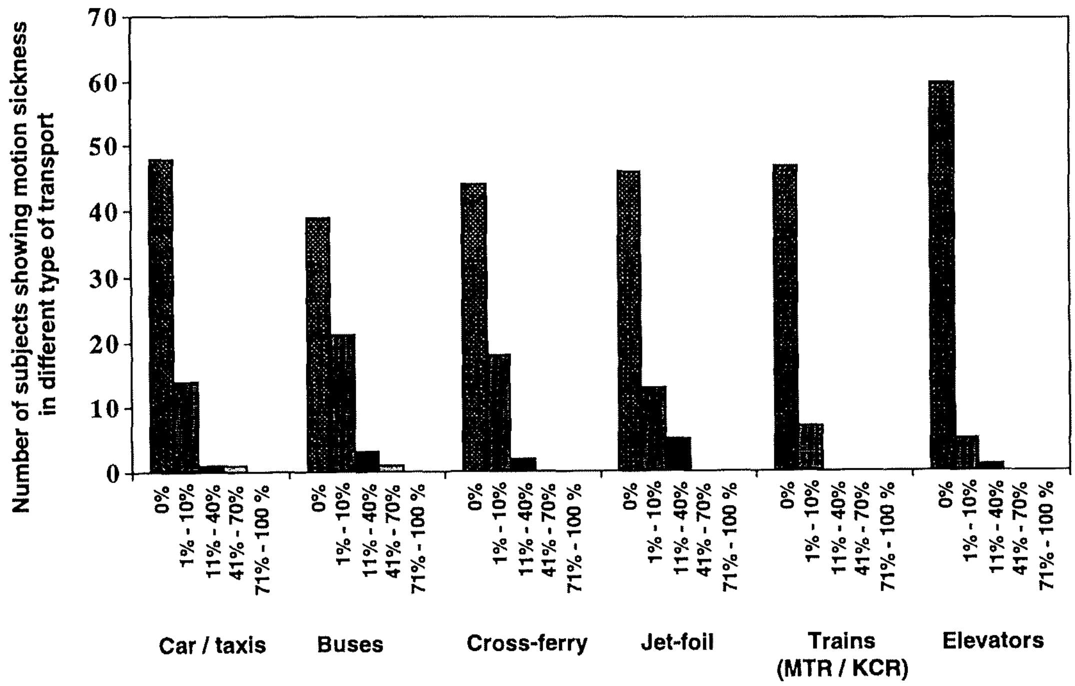


Figure 8.5 Number of subjects (Experiment two) showing motion sickness while travelling as a passenger in different type of transport

Table 8.5 Number of subjects (Experiment two) showing the corresponding symptoms when they were suffering from motion sickness in different type of transport

Types of transport	Numbers of subjects showing the corresponding symptoms when they were suffering from motion sickness in this type of transport				
	Sweating	Nausea	Dizziness	Headache	Vomiting
Cars/Taxis	1	4	15	2	0
Buses	2	7	19	5	0
Cross-ferry	4	6	15	0	0
Jet-foil	2	7	12	2	0
Trains (MTR/KCR)	0	2	6	1	0
Elevators	0	1	5	2	0

In general, over 60% of the subjects did not experience motion sickness in cars/taxis, buses, cross-ferry, jet-foil, trains and elevators in the past 12 months respectively. For those who experienced motion sickness in these transports, the most frequently reported option was '1% - 10%' and the percentage was: 87.5 % in car/taxis; 84% in buses; 90% in cross-ferry; 72% in jet-foil, 100% in trains and 83% in elevators. Besides, Table 8.5 illustrates that 'Dizziness' was the most frequently reported symptom in all types of transport.

Question 3 of the motion sickness history questionnaire measured the subjects' motion sickness susceptibility. It classified subjects into 5 different groups: 'Not at all'; 'Slight'; 'Moderately'; 'Very'; and 'Extremely'. Table 8.6 summarizes the numbers of subjects being classified into different groups of motion sickness susceptibility of each condition individually.

Table 8.6 Numbers of subjects (Experiment two) being classified into different groups of motion sickness susceptibility of each scene velocity condition individually

Scene velocity	Numbers of subjects being classified into different groups of motion sickness susceptibility				
	Not at all	Slight	Moderately	Very	Extremely
Level 1	1	9	2	0	0
Level 2	1	9	2	0	0
Level 3	1	9	2	0	0
Level 4	1	9	2	0	0
Level 5	2	8	2	0	0

The results of question 3 indicated that, the motion sickness susceptibilities of the 5 conditions were about the same. Correlation was performed between the score of motion sickness susceptibility and the nausea ratings after 30 minutes of the simulation (highest nausea ratings). The correlation coefficient r=0.19282 with p=0.1391, it suggested that there was no significant correlation between nausea ratings and motion sickness susceptibility.

8.7.3 The simulation assessment results

Analysis of variance were carried out, the scene velocity did not show a significant effect in the answers to question 1 (Q1: Did you feel you were moving during the experiment?), the answers to question 2 (Q2: How uncomforted of HMD?), the answers to question 3 (Q3: How completely did you believe you were part of virtual environment?) and the answers to question 5 (Q5: How excited do you feel after the experiment?), (Q1:$F(4,55)=0.57$, $p=0.6836$; Q2: $F(4,55)=1.22$, $p=0.3125$; Q3: $F(4,55)=1.81$, $p=0.1409$; Q5: $F(4,55)=1.15$, $p=0.3418$).But the scene velocity anticipated significant effects on the answers to question 4 (Q4: How flat and missing in depth did the world appear?) ($F(4,55)=2.57$, $p=0.0481$) and the answers to question 6 (Q6: How real was the graph simulation?) ($F(4,55)=3.1$, $p=0.0255$). The ANOVA results were summarized in Appendix Q: Table Q.22.

In addition, correlation was performed among the answers to the 6 questions with the nausea ratings and apparent self-motion ratings after 30 minutes of the simulation. The answer to question 1 (Q1: Did you feel you were moving during the experiment?) showed a strong correlation with nausea ratings and apparent self-motion ratings after 30 minutes of the simulation (r= 0.6832, p=0.0001; r= 0.8783, p=0.0001 respectively). This result confirms the sensory conflict theory once more – the stronger the perception of vection, the higher the rated level of cybersickness. Besides, although the correlation coefficient (r) between the answers to question 3 (Q3: How completely did you believe you were part of virtual environment?) and the answers to question 1 (Q1: Did you feel you were moving during the experiment?) was equal to 0.44517, the p value was 0.0004. It suggested that the higher the perceived sense of presence in the virtual environment, the higher the perception of apparent movement.

8.8 Summary

Over the 30 minutes immersive VR simulation presented via a head-mounted display, both nausea ratings and apparent self-motion ratings increased with exposure duration. Levels of cybersickness (nausea) increased significantly ($p<0.001$) with increasing scene velocity (e.g. 3.4m/s r.m.s. to 24 m/s r.m.s. in fore-and-aft axis). Besides, nausea ratings showed a strong correlation with apparent self-motion ratings (r=0.81267, p=0.0001). It indicated that higher perception of vection can cause higher rated level of nausea in VR users. This is consistent with the sensory conflict theory.

The results of motion sickness questionnaires suggested that there were no correlated relationship between the level of reported nausea ratings and the self-rated susceptibility of motion sickness. This agrees with the finding of Experiment one.

Analysis of pre and post immersive symptom checklist suggested that the sickness profiles might be functions of scene velocity. In addition, the levels of apparent self-motion cease to increase after a critical value of scene velocity (e.g. about 25m/s for translational scene movement). There is a trend for the Disorientation sub-score to increase with increasing scene velocity. A possible reason is that, when the scene is moving in a very high velocity, people cannot see what is being presented in the scene clearly and cause dizziness and vertigo. Since, dizziness and vertigo are within the Disorientation sub-score, therefore, the score increases as scene velocity increases.

The results of the simulation assessment questionnaires indicated that the higher the rated levels of sense of presence in the virtual environment, the higher the rated levels of apparent movement (or illusion of movement).

All in all, the result of this experiment has confirmed that scene velocity can significantly influence the nausea levels resulted from cybersickness occurrence.

Chapter 9 Studies of effects of scene complexity on cybersickness with a head-coupled virtual reality system (Experiment three)

9.1 Purpose of this experiment

Scene complexity is one of the two main components of the proposed 'spatial velocity' metric for quantifying scene movement. It is important to conduct an experiment to confirm that scene complexity will influence the level of cybersickness.

9.2 Objective and hypothesis

An experiment was conducted to study the effects of scene complexity on cybersickness. The specific objective was to determine the relationship between scene complexity and the rated level of cybersickness. It is hypothesized that the higher the visual scene complexity will produced higher rated level of cybersickness.

9.3 Dependent and independent variables

In this study, two independent variables were: (i) duration of exposure to virtual reality simulation (0 to 30 minutes), (ii) scene complexity (3 different levels: high, medium and low). Table 9.1 summarizes the spatial frequencies, scene velocities and spatial velocities of the three conditions. The scene velocities of the 3 conditions were the same. The time history curves of scene displacements and scene velocities of the 3 conditions are shown in Appendix O. Five representative snapshots of the 3 different scene complexity conditions are shown in Figure 9.1, 9.2 and 9.3 respectively.

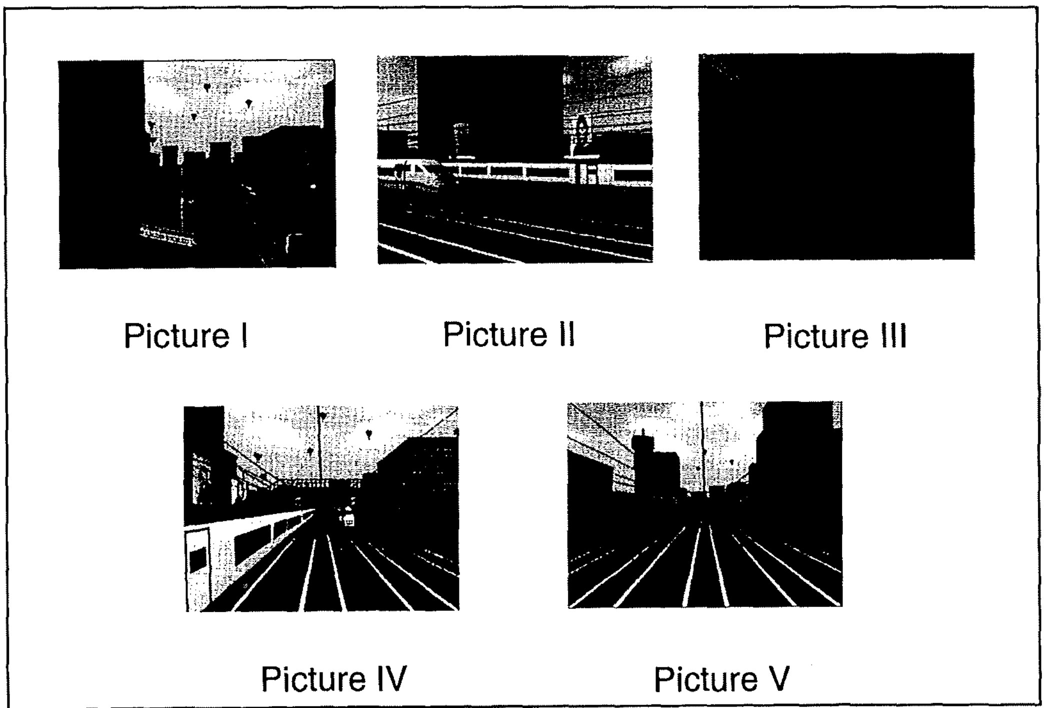


Figure 9.1 Five representative snapshots of high scene complexity condition

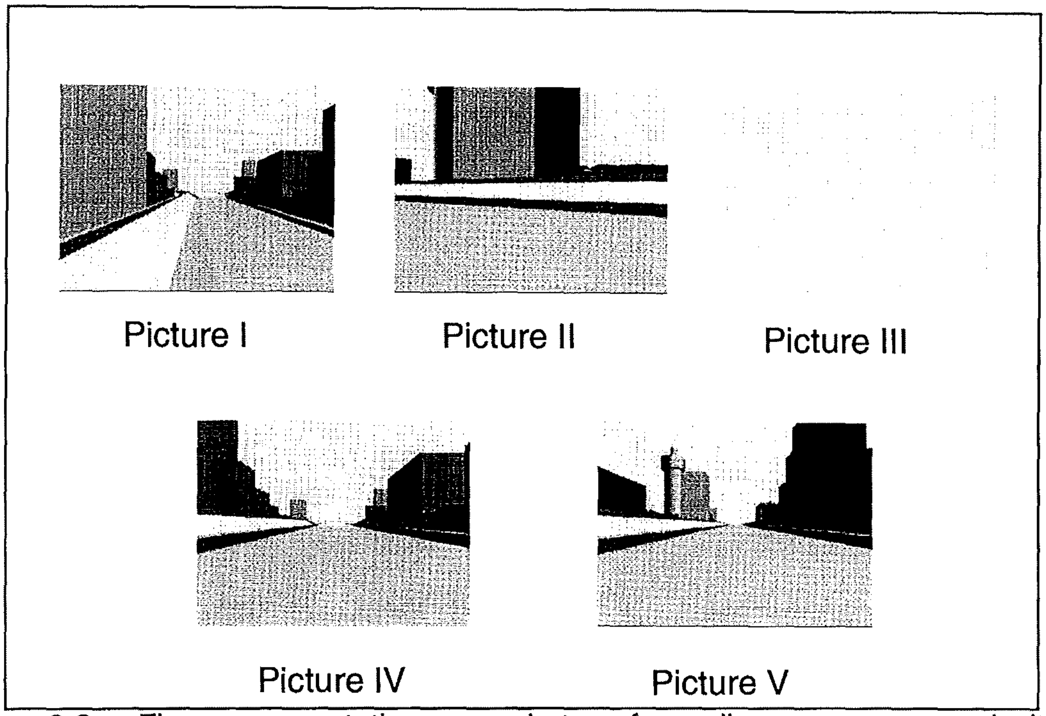


Figure 9.2 Five representative snapshots of medium scene complexity condition

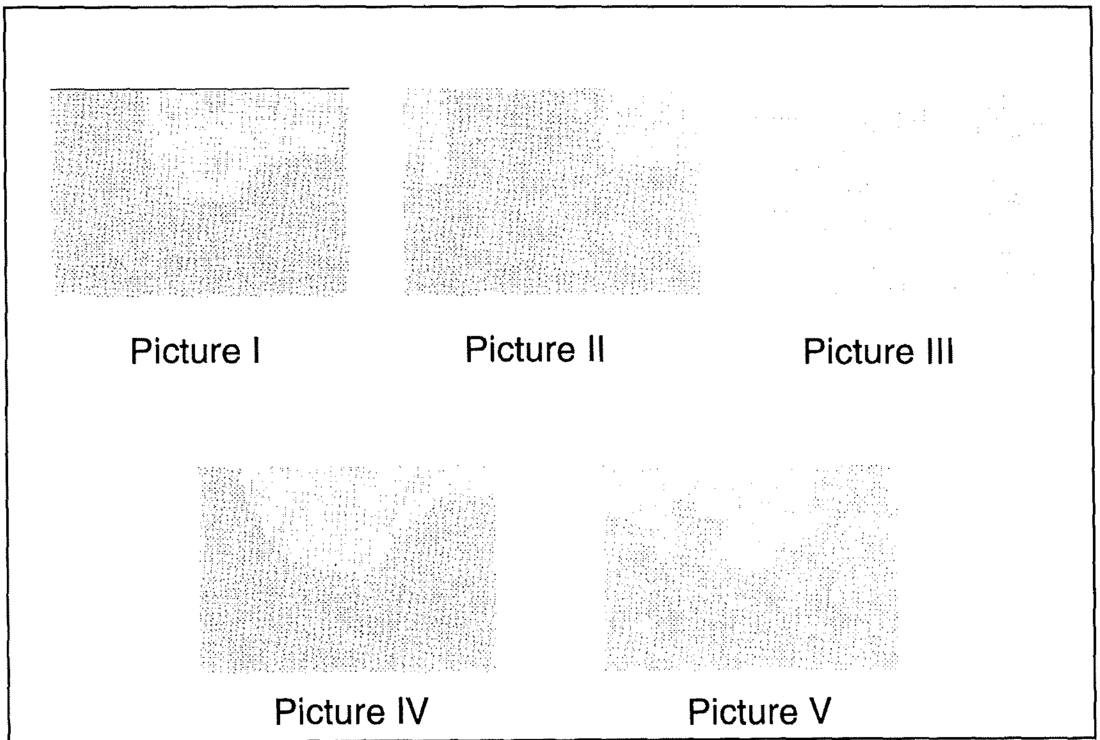


Figure 9.3 Five representative snapshots of low scene complexity condition

Table 9.1 Spatial frequencies, scene velocities and spatial velocities of the three scene complexity conditions

<table>
<tr><td colspan="3" rowspan="2"></td><td colspan="3">Level of scene complexity</td></tr>
<tr><td>High</td><td>Medium</td><td>Low</td></tr>
<tr><td rowspan="6">r.m.s scene velocity [v]</td><td rowspan="3">Translational (m/s)</td><td>X-axis</td><td colspan="3">9.5944</td></tr>
<tr><td>Y-axis</td><td colspan="3">3.1137</td></tr>
<tr><td>Z-axis</td><td colspan="3">0.5919</td></tr>
<tr><td rowspan="3">Rotational (deg/s)</td><td>Roll</td><td colspan="3">1.4143</td></tr>
<tr><td>Pitch</td><td colspan="3">1.6331</td></tr>
<tr><td>Yaw</td><td colspan="3">10.9898</td></tr>
<tr><td rowspan="3">Spatial frequency [SF]</td><td colspan="2">Horizontal (cyc/deg)</td><td>0.1556</td><td>0.03358</td><td>0.00338</td></tr>
<tr><td colspan="2">Vertical (cyc/deg)</td><td>0.1338</td><td>0.03038</td><td>0.0002</td></tr>
<tr><td colspan="2">Radial (cyc/deg)</td><td>0.2086</td><td>0.04588</td><td>0.00338</td></tr>
<tr><td rowspan="6">Spatial Velocity [SV]</td><td rowspan="3">Translational (cyc·m/s·deg)</td><td>X-axis</td><td>2.0014</td><td>0.44019</td><td>0.03243</td></tr>
<tr><td>Y-axis</td><td>0.4844</td><td>0.10456</td><td>0.01052</td></tr>
<tr><td>Z-axis</td><td>0.0792</td><td>0.01798</td><td>0.00012</td></tr>
<tr><td rowspan="3">Rotational (cyc/s)</td><td>Roll</td><td>0.2950</td><td>0.0649</td><td>0.0048</td></tr>
<tr><td>Pitch</td><td>0.2186</td><td>0.0496</td><td>0.0003</td></tr>
<tr><td>Yaw</td><td>1.7096</td><td>0.3690</td><td>0.0371</td></tr>
<tr><td colspan="3">Average translational scene velocity (m/s) [X-axis+Y-axis+Z-axis]</td><td colspan="3">4.4333</td></tr>
<tr><td colspan="3">Average rotational scene velocity (deg/s) [Pitch+Yaw+Roll]</td><td colspan="3">4.67907</td></tr>
<tr><td colspan="3">Average translational spatial velocity (cyc·m/s·deg) [X-axis+Y-axis+Z-axis]</td><td>0.8550</td><td>0.18758</td><td>0.01436</td></tr>
<tr><td colspan="3">Average rotational spatial velocity (cyc/s) [Pitch+Yaw+Roll]</td><td>0.74106</td><td>0.16118</td><td>0.01408</td></tr>
</table>

During the virtual guided tour simulation, subjects would travel through a virtual city passively on a pre-determined close loop path. The motion of the path contained movement in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes.

The simulation took place in a darkened environment so that the only visual stimulus came from the VR4 head-mounted display. The laboratory was air-conditioned in order to eliminate the temperature and ventilation variables. The temperature of the room was kept at about 23°C and the relativity humidity was about 58%.

The dependent variables were: (i) the level of sickness rating, (ii) level of apparent self-motion (vection) ratings, (iii) sickness symptoms and (iv) rated realism of simulation. A motion sickness history questionnaire (Appendix K) was used to estimate subjects' susceptibility to motion sickness. The questionnaire was developed by R.H.Y. So and Colleen Finney and has been used in an internal course project in the IEEM department of HKUST (1997).

Before the simulation, subjects were asked to complete a symptom checklist containing 27 items (adapted from Kennedy *et al.*, 1993, see Appendix B). After the simulation, subjects were required to fill out this checklist again to compare reported symptoms before and after simulation.

A seven point subjective rating scale (adapted from Golding and Kerguelen, 1992) was used to measure the level of unpleasant feeling during the simulation (see Appendix C). This scale ranged from 'no symptom' to 'moderate nausea' scale. A four point subjective rating scale (see Chaper 8: Table 8.2) was used to measure the level of apparent self-motion (vection) during the virtual simulation.

After the 30 minutes experiment, the realism of the virtual environment was measured using a simulation assessment questionnaire (modified from Regan and Price, 1993a, see Appendix D).

9.4 Apparatus and virtual reality software

The simulation was developed using a virtual reality authoring software (dVISE) running on a Silicon Graphics ONYX2 workstation. The general arrangement of experimental apparatus is described in Chapter 7: Figure 7.3. A Polhemus 3-SPACE magnetic tracker was used to measure head position and orientation at 30 samples per second. This tracker was mounted on top of a head-mounted display (VR4: 48° horizontal 36° vertical).

Same visual scenes were presented to both eyes and the images completely overlaid each other (i.e. biocular images). The images were focused at around 2 feet in front of the display and were continuously updated according to head orientation at 30 frames per second. The weight of the head-mounted display was 0.935kg and the pixel resolution was 742 (horizontal) 230 (vertical).

9.5 Visual scene content of the simulation

During the 30 minutes simulation, the visual scene of high complexity condition consisted of some buildings, several railways, power lines, a train station, trains, workers, some billboards, bridges, grasslands, traffic lights and a blue sky with some white clouds.

The visual scene of medium complexity condition consisted of some building, lands, a bridge and a blue sky.

The visual scene of low complexity condition consisted some buildings, lands and a blue sky. The color of the buildings, lands were about the same (pale blue).

9.6 Method and Design

Thirty-six male Chinese volunteers participated in the experiment. They were staffs and students of the Hong Kong University of Science and Technology (age: 19 to 39). They were randomly assigned to one of the 3 conditions. Each condition had 12 subjects participated. Three levels of scene complexity were investigated in this experiment: The spatial frequencies, scene velocities and spatial velocities of the 3 conditions are summarized in Table 9.1. All experimental procedures were the same in the 3 conditions, except the scene complexity. During each condition, subjects would be exposed to a 30 minutes virtual reality simulation. Before the subjects participated the experiment, they were asked to complete a colorblindness test and a motion sickness history questionnaire. All subjects received HK$50 to compensate for their time.

The 36 subjects were briefed about the experiment and were then asked to read and sign a consent form. They were informed that they could withdraw from the experiment at any time on request and under no obligation to give reasons for withdrawal or to attend again for experimentation. At the beginning of the experiment, subjects were asked to rest for five minutes to minimize any unwanted influence from previous activities. The subjects were then required to complete a 'sickness symptom checklist', adapted from Kennedy (1993) (Appendix B). The inter pupillary distance of the subjects was measured prior to their data sessions so that the distance between left and right display of the head-mounted display (HMD) could be adjusted accordingly. Subjects would then put on the HMD and one minute practice was given to the subjects to familiarize themselves with the equipment. During this one minute practice, subjects were allowed to move their heads to inspect the virtual environment that they were 'immersed' in. Subjects remained seated throughout the simulation. The chair they sat had a back-rest, a lumber support and two arm-rests. Before the simulation, the height of the chair was adjusted according to the subjects' preference. In this study, the scene motions were controlled during the 30 minutes of the simulation. At 30 seconds intervals from the start of the simulation, subjects were asked verbally to turn their heads to the right (about 55°~65°) and then face straight again. Further 30 seconds they were verbally asked to turn their heads to the left (55°~65°) and then face straight again. These kind of discrete head movements were repeated over the whole 30 minutes simulation. At five-minute intervals from the start of the simulation, subjects were verbally asked to rate their symptoms of nausea on a seven-point nausea scale (Appendix C) and level of apparent self-motion (vection) on a four-point scale (Chapter 8: Table 8.2). After the simulation session, the subject were asked to complete another 'sickness symptom checklist' and a 'simulation assessment questionnaire' (Appendix D).

9.7 Result and Discussion

9.7.1 Results of sickness ratings and symptoms in three different levels of scene complexity

9.7.1.1 Effects of scene complexity and duration on nausea ratings

A two factors (scene complexity * duration) ANOVA was performed for the dependent variable of nausea ratings (see Appendix R: Table R.1). There was significant interaction between the two factors ($F(12,231)=1.84$, $p=0.0426$). The ANOVA result illustrated that, scene complexity anticipated significant effect on nausea ratings ($F(2,2321)=34.48$, $p=0.0001$). The 3 scene complexities were significantly different from each other (see Appendix R: Table R.2). The mean nausea rating of high scene complexity condition was 2.0476, while 0.9167 in medium scene complexity condition and 0.2262 in low scene complexity condition. This results pointed out that increase in scene complexity would lead to significant increase in rated level of nausea ratings. Five subjects withdrew from the experiment before the end of the experiment because they suffered from 'moderate nausea' (6 on the scale of Appendix C). These five subjects were participating in the high scene complexity condition. For the purpose of data analysis, after a subject withdrew from the experiment, a nausea rating of 6 was assigned until the end of the simulation. Besides, the values of the apparent self-motion ratings of the time they withdrew were assigned unit the end of the end of the simulation.

Duration anticipated significant effect on nausea ratings ($F(2,231)=10$, $p=0.0001$) (see Appendix R : Table R.1). On the whole, the SNK test showed that nausea ratings were significantly different after 10 minutes of the simulation (see Appendix R: Table R.3). Besides, by investigating the effect of duration on nausea ratings of each condition individually, the mean nausea ratings increased significantly with exposure duration in all conditions (see Appendix R: Table R.4a & Table R.4b). The on-set of significant effect on nausea ratings in high scene complexity condition was after 10 minutes of the simulation, 10 minutes in medium scene complexity condition and after 25 minutes in low scene complexity condition. Although the increases were not significant even after 25 minutes of simulation in all conditions. The mean nausea ratings as function of exposure duration with stand derivation of the 3 conditions are shown in Figure 9.4

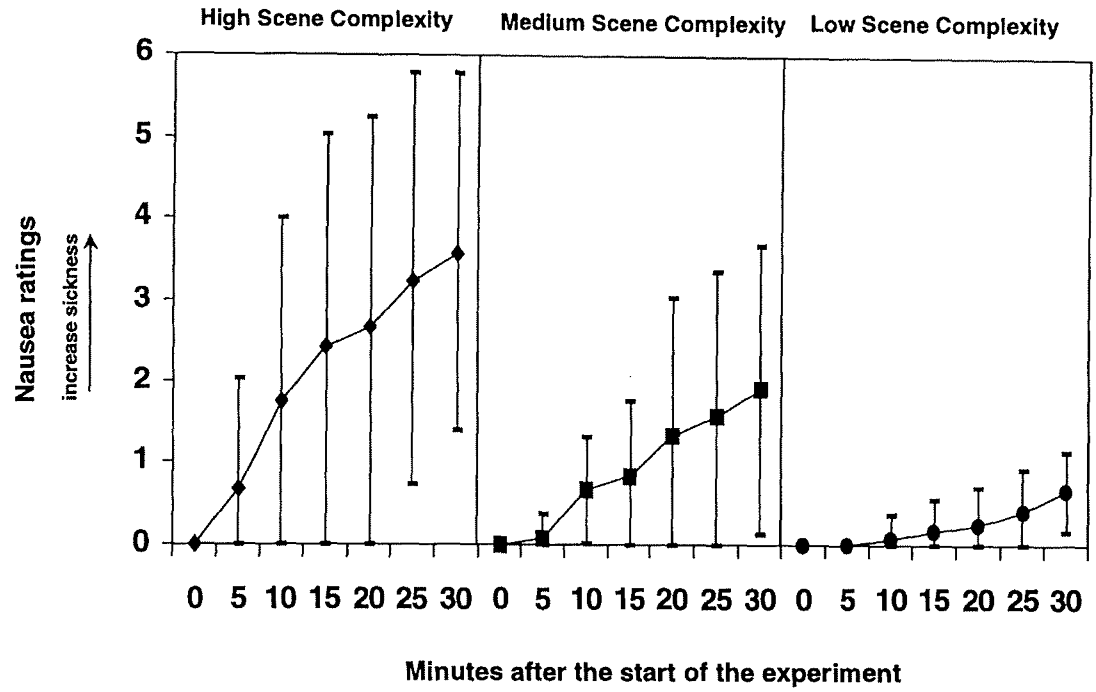


Figure 9.4 Mean nausea ratings as function of exposure duration with stand derivation of the 3 different scene complexity conditions

9.7.1.2 Effects of scene complexity and duration on apparent self-motion ratings

A two factors (scene complexity * duration) ANOVA was performed for the dependent variable of apparent self-motion ratings (see Appendix R: Table R.5). There was significant interaction between the two factors (F(12,231)=2.6, p=0.0029). Besides, the 3 different scene complexities were significantly different in apparent self-motion ratings (F(2,231)=61.71, p=0.0001). A post-hoc Student Newman Keuls (SNK) test showed that high scene complexity condition (mean of apparent self-motion rating = 1.2976) were significantly different from median scene complexity condition (mean of apparent self-motion rating = 0.3333) and low scene complexity condition (mean of apparent self-motion rating = 0.2262). In addition, The SNK test also showed that medium scene complexity condition was not significantly different from low scene complexity condition on apparent self-motion ratings (see Appendix R: Table R.6).

Duration anticipated significant effect on apparent self-motion ratings ($F(6,231)=9.37$, $p=0.0001$) (see Appendix R : Table R.5). On the whole, the SNK test showed that apparent self-motion ratings were significantly different after 5 minutes (see Appendix R: Table R.7). Besides, by investigating the effect of duration on apparent self-motion ratings of each condition individually, the mean apparent self-motion ratings increased with exposure duration in all conditions. But the increase was significant only in high scene complexity condition (see Appendix R: Table R.8a & Table R.8b). Although the increase was not significant even after 20 minutes of the simulation. In addition, the mean apparent self-motion ratings as function of exposure duration with stand derivation of the 3 conditions are shown in Figure 9.5. Scene complexity showed significant effect on nausea and apparent self-motion ratings, nausea ratings showed a strong correlation with apparent self-motion ratings ($r=8.6235$, $p=0.0001$).

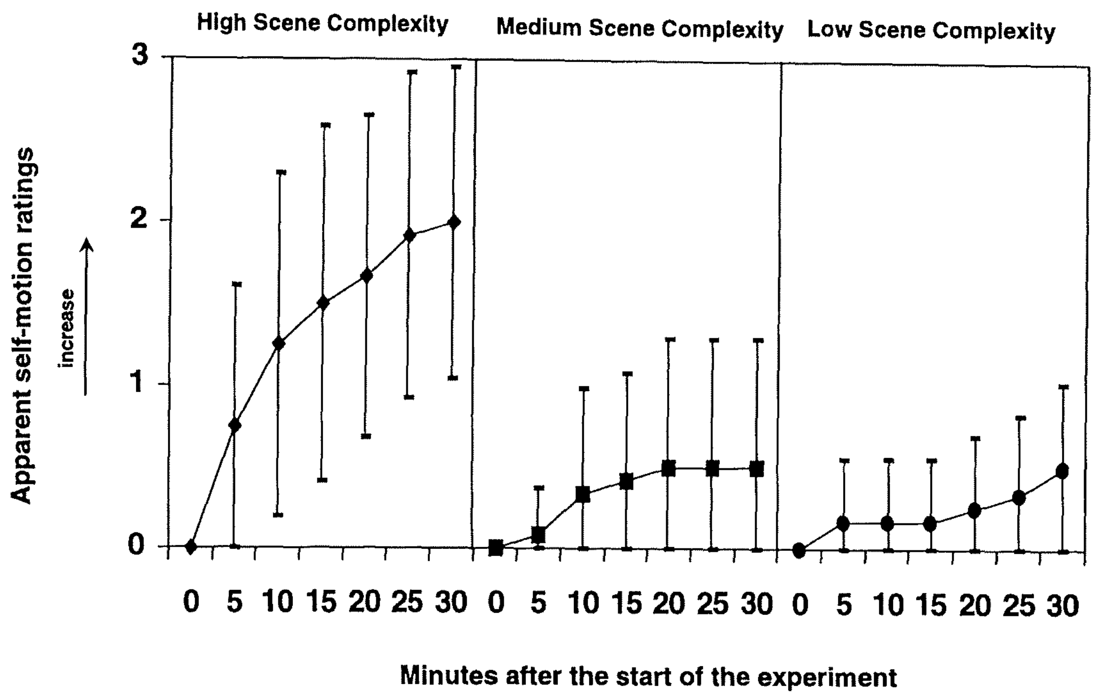


Figure 9.5 Mean apparent self-motion ratings as function of exposure duration with stand derivation (SD) of the 3 different scene complexity conditions

9.7.1.3 Comparing the sickness symptoms and profiles among the three different levels of scene complexity

The numbers of subjects who reported any symptom before and after the experiment (3 conditions) are shown in the following figures. Figure 9.6a presents the Nausea sub-scale, Figure 9.6b illustrates the Oculomotor sub-scale while the Disorientation sub-scale is described in Figure 9.6c. Figure 9.6d points out the 12 symptoms of the symptom checklist that are not classified in the three sub-scales.

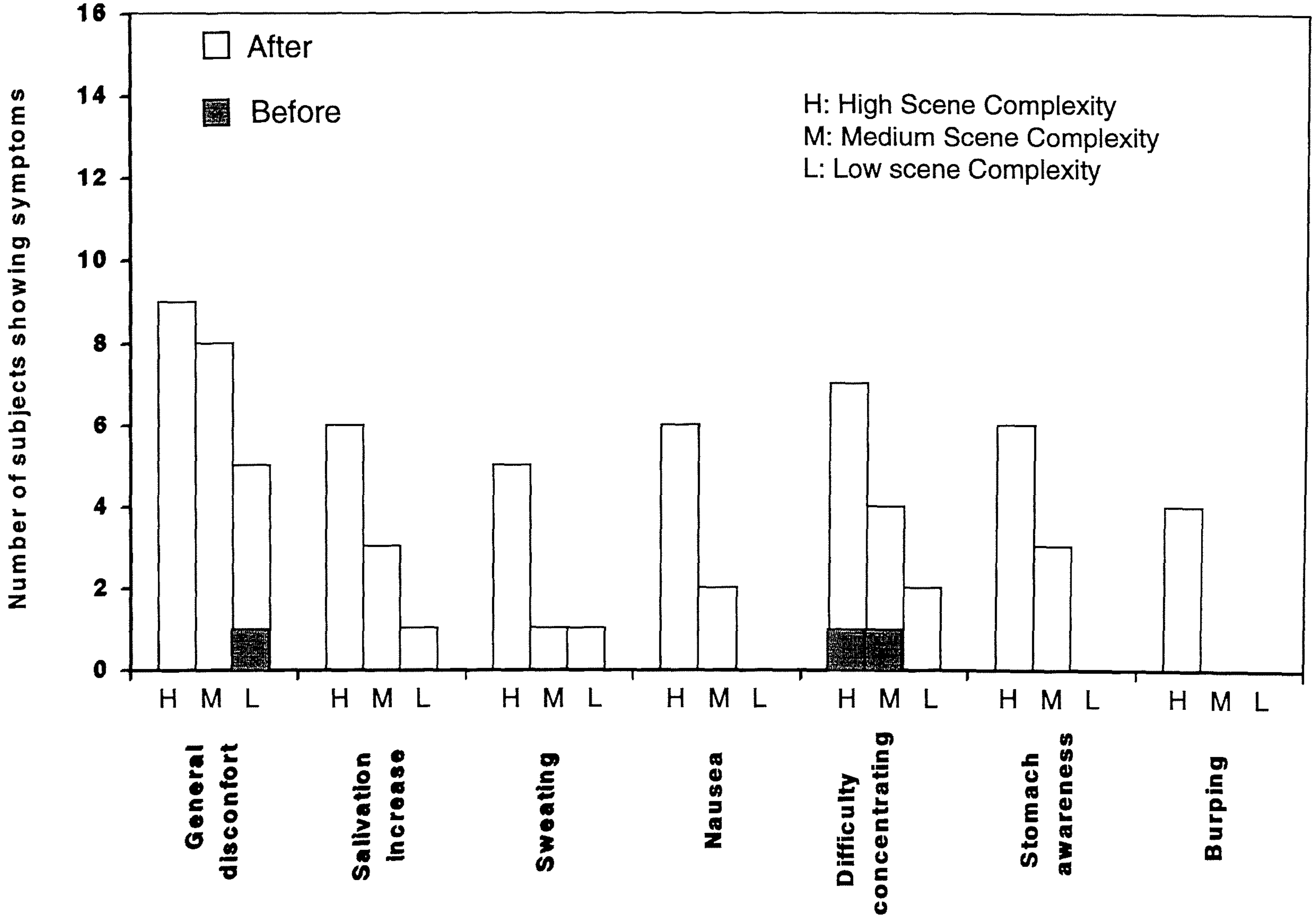


Figure 9.6a Number of subjects showing sickness symptoms (Nausea sub-scale) before and after the Experiment three

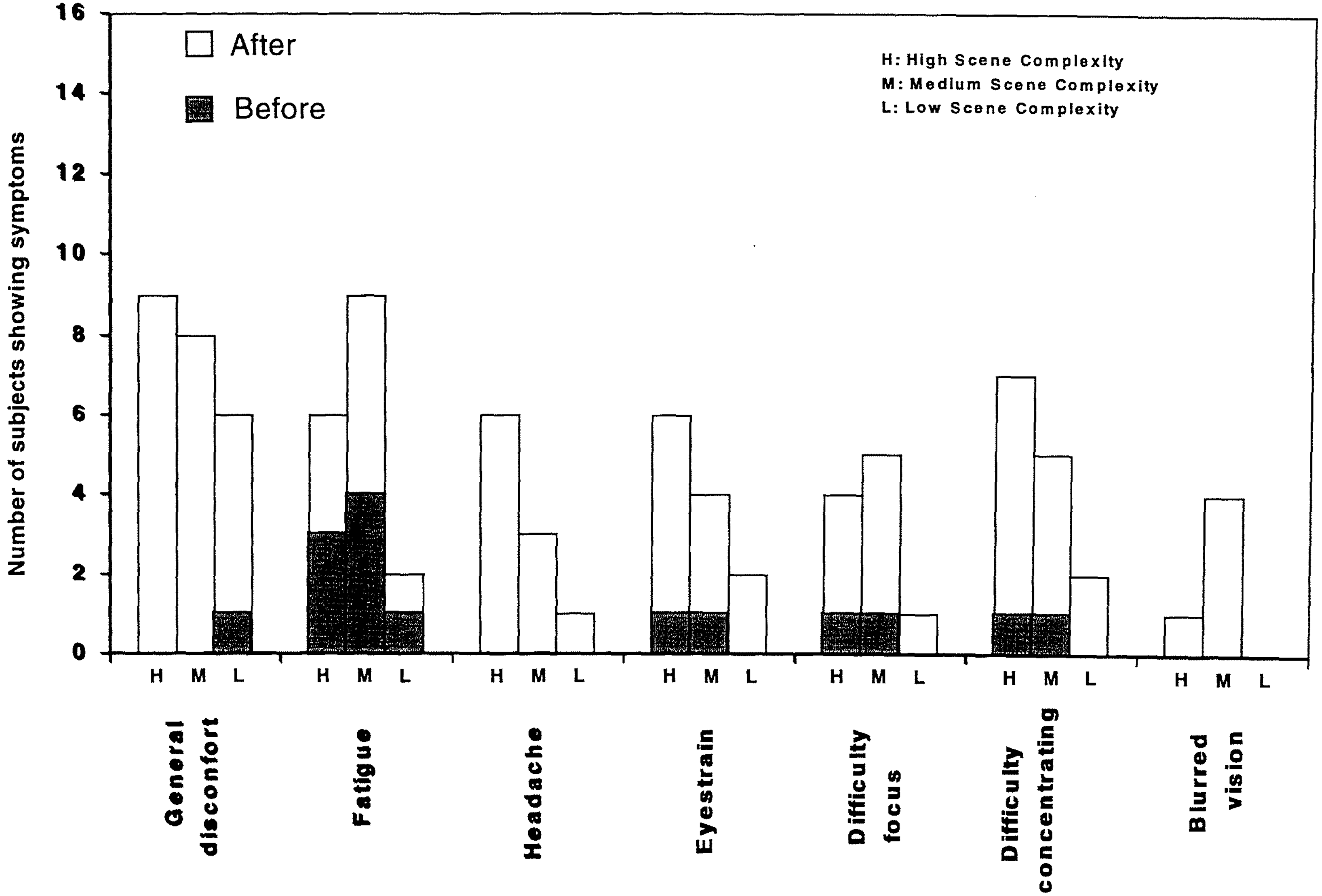


Figure 9.6b Number of subjects showing sickness symptoms (Oculomotor sub-scale) before and after the Experiment three

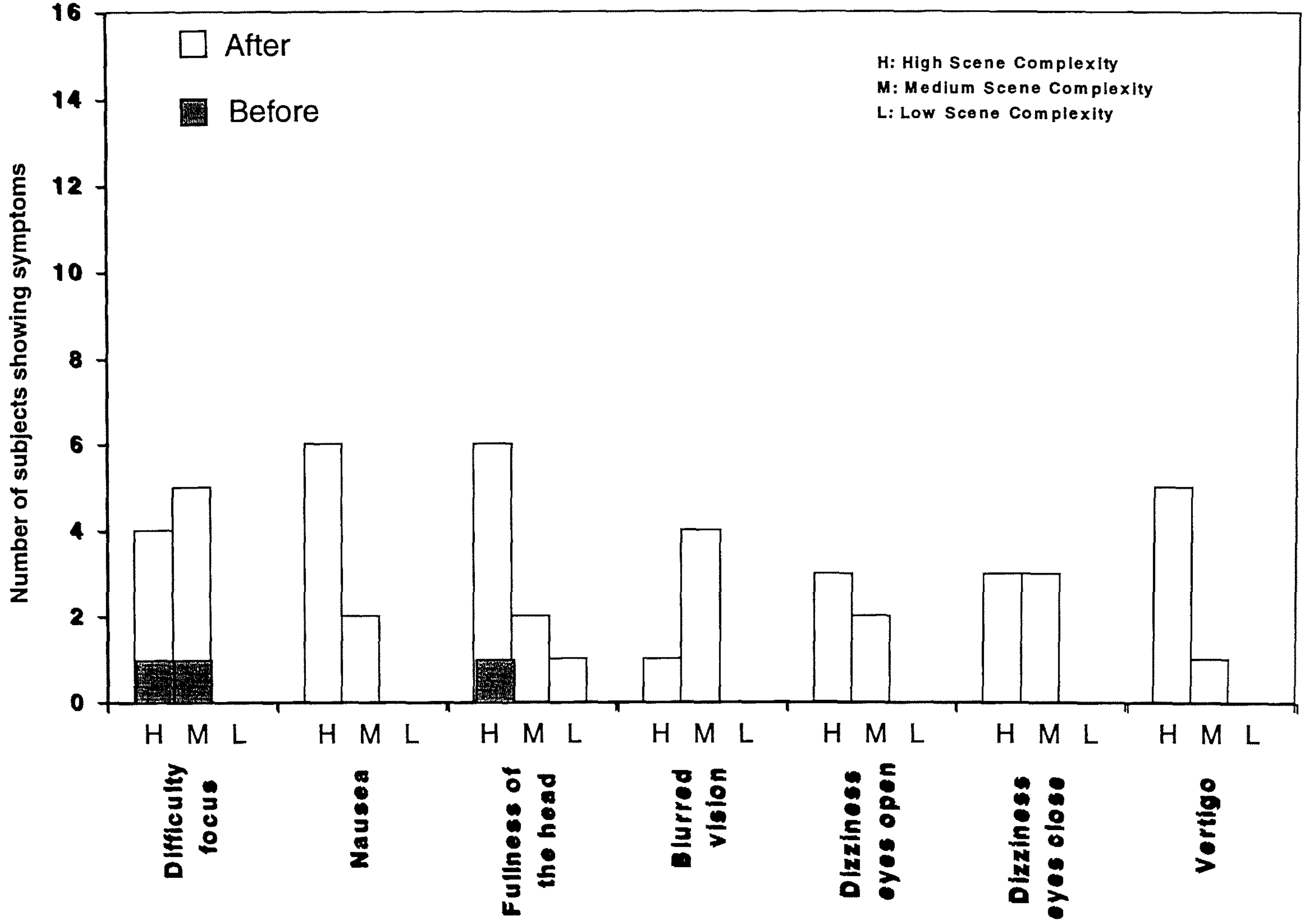


Figure 9.6c Number of subjects showing sickness symptoms (Disorientation sub-scale) before and after the Experiment three

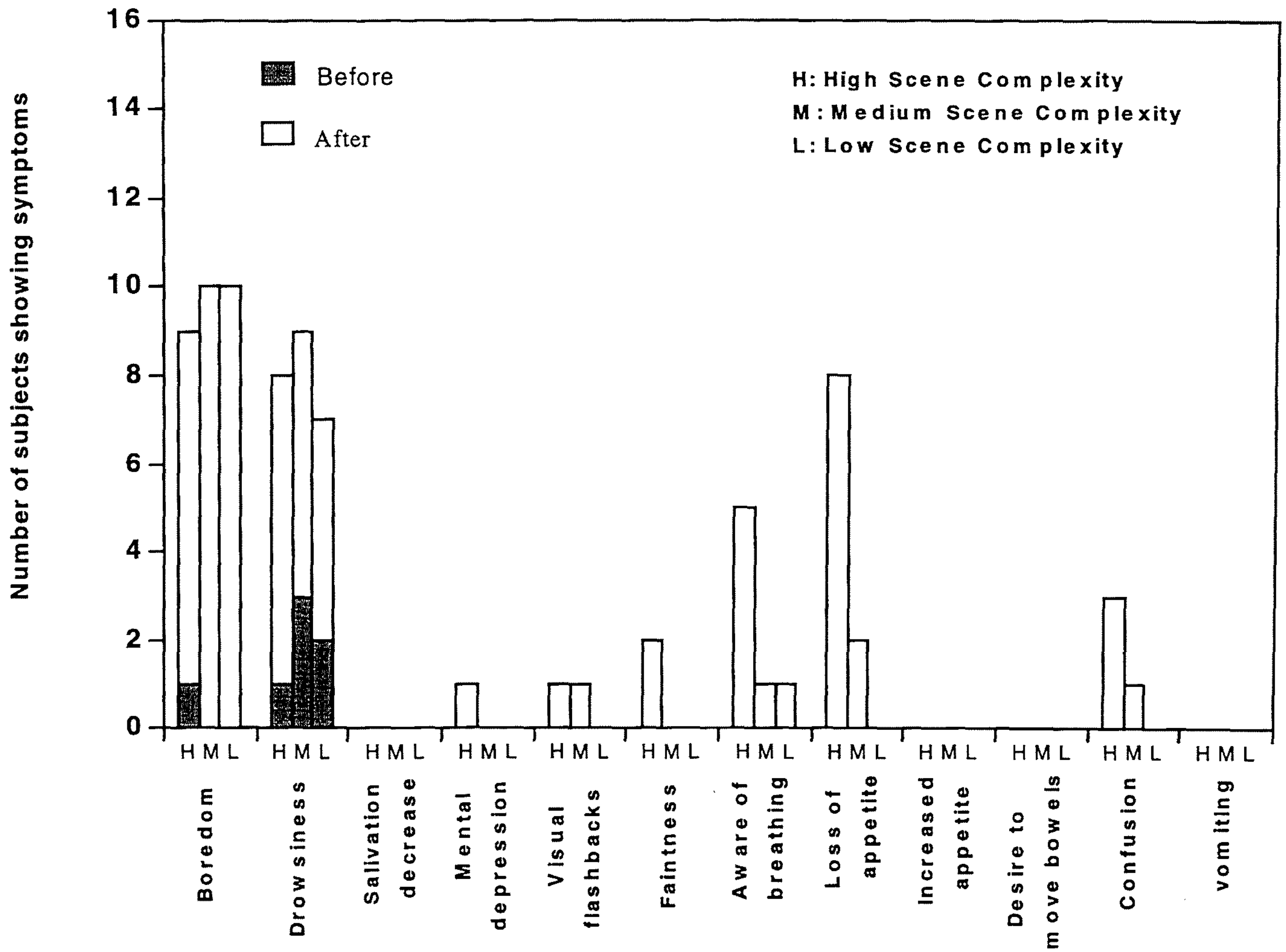


Figure 9.6d Number of subjects showing the other 12 symptoms (not classified in the three sub-scale) before and after the Experiment three

Comparing the 'general discomfort' with other symptoms in Nausea sub-scale (see Figure 9.6a). It was the mostly reported symptoms (more subjects suffered from it after the experiment). Besides, 'difficulty concentrating' was the second most frequently reported symptom. Figure 9.6b shows that 'general discomfort' and 'fatigue' were frequently reported in all conditions. Figure 10.6c illustrates that 'difficulty focus' and 'fullness of the head' were frequently reported symptoms in the Disorientation sub-scale. Figure 9.6d illustrates that 'boredom' and 'drowsiness' were also frequently reported.

Figure 9.7 illustrates the pre-immersion, post-immersion and change sickness profiles (difference between pre and post) for all subjects in the experiment (3 conditions). The descriptive statistics are shown in Appendix R: Table R.9. By investigating the pre-immersion profile, there were not significantly different on Nausea sub-score (N), Oculomotor sub-score (O), Disorientation sub-score (D) and Total Sickness Score (TS) among the 3 different levels of scene complexity (N: $F(2,33)=0$, $p=1$; O: $F(2,33)=1.09$, $p=0.3465$; D: $F(2,33)=1.06$, $p=0.3564$; TS: $F(2,33)=0.90$, $p=0.4171$, see Appendix R: Table R.10, R.11, R.12, R.13 respectively). This result indicated that, subjects in different conditions were equally healthy before participating in the experiment. By comparing the post immersion with pre-immersion sickness profiles of high and medium scene complexity conditions individually, the sub-score of Nausea (N), Oculomotor (O), Disorientation (D) and Total Sickness score (TS) were significantly different (see Appendix R: Table R.14, R.15, R.16 & R.17). While in the low scene complexity condition, Nausea (N), Oculomotor (O) sub-scores and Total sickness score were significant different between the pre and post immersion. But the pre and post Disorientation sub-score were not significantly different (F(1,22)=2.20, p=0.1522). The result showed that after the 30 minutes virtual guided tour simulation, it made subjects feel uncomfortable.

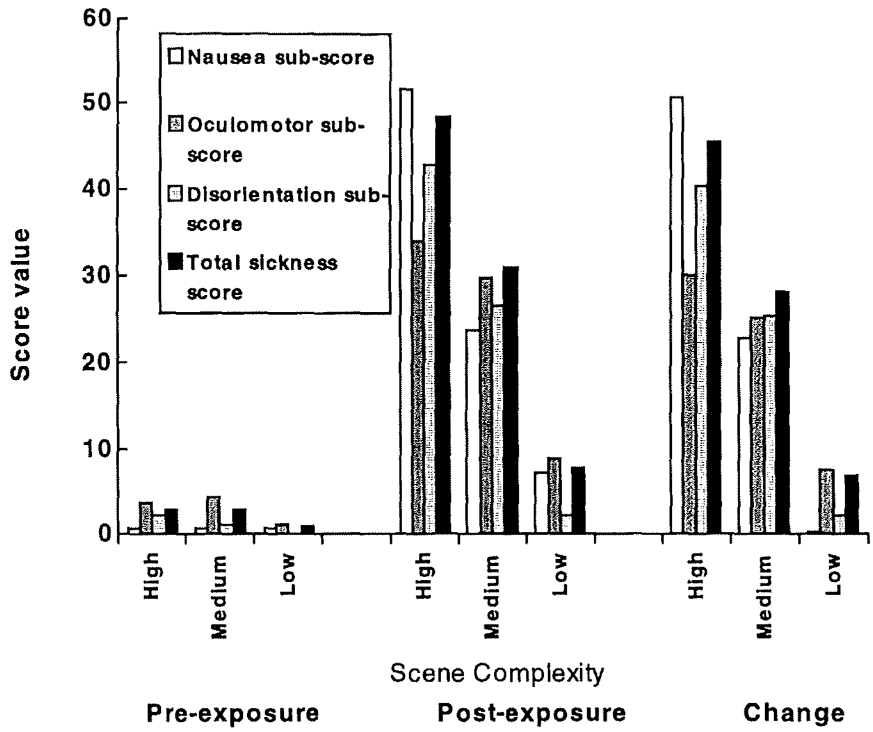


Figure 9.7 Illustration of the pre-immersion, post-immersion and change sickness profiles of the 3 scene complexity conditions

The change sickness profiles were distinguishable between the 3 conditions. Table 9.2 summarizes the ranking of the three sub-scores for each conditions.

Table 9.2 Ranking of Nausea, Oculomotor and Disorientation sub-scores for the 3 scene complexity conditions

Scene complexity	Ranking of Nausea (N), Oculomotor (O) and Disorientation (D) sub-scores
High	N (mean: 50.8800) > D (mean: 40.6000) > O (mean: 35.3733)
Medium	D (mean: 26.6800) > O (mean: 25.2667) > N (mean: 23.0550)
Low	O (mean: 7.5800) > N (mean: 6.3600) > D (mean: 2.3200)

According to the table, the shape of sickness profiles may be related to the level of scene complexity. Different scene complexity may give different sickness profiles.

Table 9.3 summarizes the ranking of Total Sickness score (TS)of the change profiles among the 3 different scene complexity conditions.

Table 9.3 Ranking of Total Sickness score (TS) of the change profiles among the 3 different scene complexity conditions

Order	Level of scene complexity with the value of the Total Sickness score (TS) of the change profiles
1st	High (TS = 45.8150)
2nd	Medium (TS = 28.3617)
3rd	Low (TS = 6.8567)

In addition, the results of ANOVA reported that scene complexity anticipated significant effect in Nausea (N), Oculomotor (O), Disorientation (O) sub-scores and the Total Sickness score (TS) in the change sickness profiles (N: $F(2,33)=7.05$, $p=0.0028$; O: $F(2,33)=4.12$, $p=0.0253$; D: $F(2,33)=5.2$, $p=0.0109$; TS: $F(2,33)=5.82$, $p=0.0068$; see Appendix R : Table R.18, R.19 R.20 & R.21). Post-hoc SNK tests showed that high scene complexity condition led to high Nausea, Oculomotor and Disorientation problems to the subjects (see Appendix R Table R.22, R.23, R.24 and R.25 respectively). Besides, the low scene complexity condition introduced less Nausea, Oculomotor, and Disorientation problem to the subjects compared with the high and medium scene complicity conditions.

9.7.2 The motion sickness history questionnaire results

Question 1 of the motion sickness history questionnaire (Appendix K), asked the percentage that the subjects have experienced motion sickness while travelling as a passenger in car/taxi, buses, cross-ferry, jet-foil, train (MTR/KCR) and elevators in the past 12 months. The number of subjects showing motion sickness while travelling as a passenger in these different types of transport are shown in Figure 9.8 while Table 9.4 illustrates the number of subjects showing the corresponding symptoms experienced while travelling as passenger in these different type of transports.

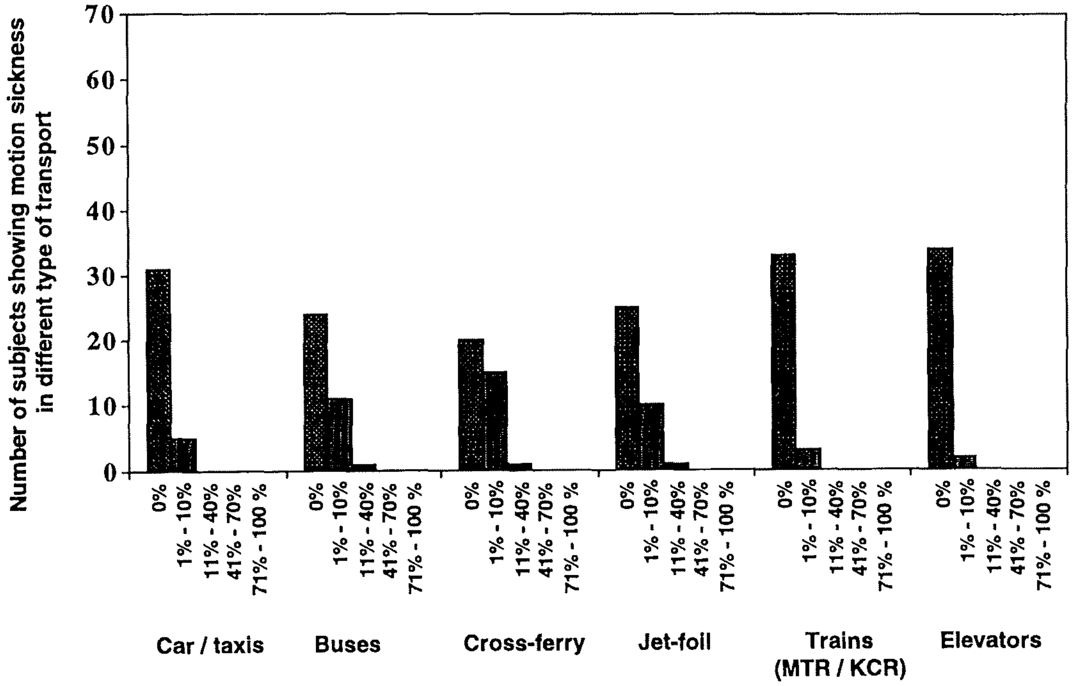


Figure 9.8 Number of subjects showing motion sickness while travelling as a passenger in different type of transport

Table 9.4 Number of subjects showing the corresponding symptoms while they suffering from motion sickness in different type of transport

Types of transport	Number of subjects showing the corresponding symptoms while they suffering from motion sickness in this type of transport				
	Sweating	Nausea	Dizziness	Headache	Vomiting
Cars/Taxis	0	2	5	1	0
Buses	2	5	6	2	0
Cross-ferry	2	4	10	3	1
Jet-foil	0	2	6	0	0
Trains (MTR/KCR)	0	1	1	1	0
Elevators	0	1	1	0	0

In general, over 55% subjects did not experience motion sickness in cars/taxis, buses, cross-ferry, jet-foil, trains and elevators in the past 12 months respectively. For those who experienced motion sickness in these transports, the most frequently reported option was '1% - 10%' and the percentage were: 100 % in car/taxis; 91.7% in buses; 93.8% in cross-ferry; 90.9% in jet-foil, 100% in trains and 100% in elevators. Table 9.5 illustrates that 'Dizziness' was the most frequently reported symptom in all types of transport.

Question 3 of the motion sickness history questionnaire measured the subjects' motion sickness susceptibility. It classified subjects into 5 different groups: 'Not at all'; 'Slight'; 'Moderately'; 'Very'; and 'Extremely'. Table 9.5 summarizes the numbers of subjects being classified into different groups of motion sickness susceptibility of each condition individually.

Table 9.5 Numbers of subjects being classified into different groups of motion sickness susceptibility of each scene velocity condition individually

Scene complexity	Numbers of subjects being classified into different groups of motion sickness susceptibility groups				
	Not at all	Slight	Moderately	Very	Extremely
High	1	9	2	0	0
Medium	1	9	2	0	0
Low	1	9	2	0	0

The results of question 3 indicated that, the motion sickness susceptibilities of the 3 conditions were about the same. Correlation was performed between the score of motion sickness susceptibility and the nausea ratings 30 minutes of the simulation. The correlation coefficient r=0.0512 with p=0.766, it suggested that there was no significant correlation between nausea ratings and motion sickness susceptibility.

9.7.3 The simulation assessment results

Analysis of variance was carried out, the scene complexity did not show significant effect on the answers to question 2 (Q2: How uncomforted of HMD?) ($F(2,33)=1.34$, $p=0.2764$). But scene complexity anticipated significant effects on the answers to question 1 (Q1: Did you feel you were moving during the experiment?), the answers to question 3 (Q3: How completely did you believe you were part of virtual environment?), the answers to question 4 (Q4: How flat and missing in depth did the world appear?), the answers to question 5 (Q5: How excited do you feel after the experiment?), and the answers to question 6 (Q6: How real was the graph simulation?) (Q1:$F(2,33)=10.83$, $p=0.0002$; Q3: $F(2,33)=11.59$, $p=0.0002$; Q4: $F(2,33)=6.48$, $p=0.0042$; Q5: $F(2,33)=3.59$, $p=0.0389$; Q6: $F(2,33)=47.75$, $p=0.0001$). The ANOVA results are summarized in Appendix R: Table R.26 and the SNK results .are illustrated in Appendix R: Table R.27. In conclusion, in the high scene complexity condition, subjects perceived higher level of vection and sense of presence in the virtual environment. Beside the rated level of realism in the high scene complexity was the highest. It might because, in the high scene complexity condition, the buildings were mapped with some real pictures of buildings on them. Beside the billboards were mapped with some real photos of cars and people, all these might give a stronger sense of realism to the scene.

In addition, correlation was performed among the 6 questions with the nausea ratings and apparent self-motion ratings after 30 minutes of the simulation (see Appendix R: Table R.28. the answers to question 1 (Q1: Did you feel you were moving during the experiment?) showed a strong correlation with nausea ratings and apparent self-motion rating after 30 minutes of the simulation (r= 0.8326, p=0.0001; r= 0.9076, p=0.0001 respectively). This result confirms the sensory conflict theory once more – the stronger the perception of vection, the higher the rated level of cybersickness. Besides, although the correlation coefficient (r) between the answers to question 3 (Q3: How completely did you believe you were part of virtual environment?) and the answers to question 1(Q1: Did you feel you were moving during the experiment?) was equal to 0.52053, the p value was 0.0013. It suggested that the higher the perception of sense of presence in the virtual environment, the higher the perception of moving in a dynamic virtual environment.

Furthermore, 'Believe part of virtual environment, Q3' correlated with 'Excitement Q5' (r=0.6263, p=0.0001; r=0.6671, p=0.001 respectively). 'Flat and missing in depth Q4' showed a negative correlation with 'Realism of the virtual environment' (r=r=0.5879'p=0.0002). Furthermore, 'Excitement, Q5' correlated with 'Realism of the virtual environment' (r=0.60685, p=0.0001). Nausea ratings after the simulation were found to be correlated with the rated level of realism (Q5) and the sense of presence (Q3) (r=0.51962, p=0.0014; r=0.40023, p=0.0172 respectively). This suggests that the realism might be a factor in causing visually-induced cybersickness. Further investigation of it is desirable.

9.8 Summary

Over the 30 minutes immersive VR simulation presented via a head-mounted display, both nausea ratings and apparent self-motion ratings increase with exposure duration. Besides, increase the scene complexity could significantly increase the rated levels of cybersickness ($p<0.001$). Furthermore, nausea and apparent self-motion ratings showed a significant high correlation ($r=0.86235$, $p=0.0001$).

The results of motion sickness questionnaires suggested that there were no correlation between the level of reported nausea ratings and scores on motion sickness susceptibility. This agrees with the findings of both Experiments one and two.

Analysis of pre and post immersive symptom checklist suggested that the sickness profiles could be functions of scene complexity. The Nausea sub-score increased with increasing scene complexity

Similar to Experiments one and two, the results of the simulation assessment questionnaires indicated that the higher the rated levels of sense of presence in the virtual environment, the higher the rated levels of apparent movement (or illusion of movement). Nausea ratings at 30 minutes of the simulation were found to correlate with the rated level of realism of the simulation and the sense of presence in the virtual environment.

All in all, the result of this experiment has confirmed that scene complexity can significantly influence the levels of cybersickness.

Chapter 10 General Discussion, Conclusion and Recommendations

10.1 General discussion

10.1.1 Discussion of experimental findings

As mentioned in Chapters two and three, many studies have reported and confirmed that cybersickness is a type of vection-induced motion sickness. Although studies concerning cybersickness have been reported, studies investigating the fundamental variables such as scene rotational axes were not found. In order to determine the cause of sickness, a study of the effects of scene movement in different axes is necessary. An experiment (Experiment one) has been conducted to study the effects of rotational scene oscillations in different axes on cybersickness (Chapter seven). This experiment also has a control condition in which subjects were exposed to a head-steered virtual environment without scene oscillation. The results of Experiment one showed that subjects exposed to a virtual environment with scene oscillation for a duration longer than five minutes suffered significant increase in nausea ratings. When subjects were exposed to virtual environment without scene oscillation, the increase in nausea ratings was significantly lower than those conditions with scene oscillations. This suggests that cybersickness is mainly caused by scene movement and confirms that cybersickness is vection-induced. There was a significant interaction between scene movement and duration on nausea ratings. With and without scene movement, the nausea ratings increased with duration, but the rate of increase in the present of scene movement was higher than that in the absence of scene movement. A possible reason is that, in the presence of scene movement, the inconsistent information perceived through the visual system (e.g. scene movement) and the vestibular systems (e.g. body and head movement) induce symptoms of sickness. This is consistent with the sensory conflict theory (see Chapter two). As the duration of exposure increased, the sickness symptoms accumulated, therefore, both nausea ratings and Simulator Sickness Questionnaire (SSQ) scores increased with duration. In the condition with no scene movement, there was no visual-vestibular conflict. According to the sensory conflict theory, there should be no reported sickness symptoms in this condition. However, this was not the case because slight levels of general discomfort or unpleasant symptoms could have been caused by the mere wearing of head-mounted display. As the slight unpleasant symptom accumulated over times, so were the nausea ratings (score 2 is the 'unpleasant' symptom, however slight, see Appendix C) and SSQ scores (SSQ symptoms included general discomfort, see Appendix B). In the condition without scene movement, the accumulation of sickness was mainly characterized by general discomfort rather than nausea. When sickness data obtained with and without scene oscillations were compared, significant differences were found. These differences confirmed once more that visual stimulus (e.g. scene oscillations) would significantly influence the rated level of cybersickness. Research on cybersickness should, therefore, be concentrated on the effects of visual stimulus. However, a review of literature shows that there is no quantitative unit to measure visual stimuli in a virtual environment (see Chapters two and three). A quantifying unit called 'Spatial Velocity (SV)' is proposed in Chapters five and six to quantify visual stimuli. SV is a metric to measure both the scene complexity and the speeds of navigation within a virtual environment (i.e. spatial velocity = scene complexity × scene velocity). Algorithms to measure the 'spatial velocity' of a virtual reality simulation has been documented and explained in Chapter six. In order to verify that the proposed 'spatial velocity' metric is a useful measure of scene movement for the study of cybersickness, two experiments were conducted. These two experiments studied the effect of scene velocity (Experiment two) and scene complexity (Experiment three) on rated level of cybersickness (see Chapters eight and nine). The reason for conducting these two experiments is that, if 'spatial velocity' is a useful measure to quantify scene movement for the studies of cybersickness, both of its components (i.e. scene complexity and scene velocity) should have significant effects on rated levels of cybersickness. The results of Experiments two and three suggested that increases in either scene velocity or scene complexity would significantly increase the nausea ratings and the cybersickness symptoms as measured by SSQ. Thus 'Spatial Velocity' is an appropriate quantitative metric to measure visual stimuli in a virtual environment. Besides, the results of Experiment three showed that, there was a significant interaction between scene complexity and duration on nausea and apparent self-motion ratings. This is not surprising as scene movement with higher complexity will cause higher levels of sickness and sickness can accumulate with time. Furthermore, nausea and apparent self-motion ratings were significantly correlated with each other (0.86235, p=0.0001). This is consistent with the sensory conflict theory in which cybersickness is a type of vection-induced motion sickness. According to the sensory conflict theory, the greater the conflict between the information received from the visual and vestibular systems, the higher the level of sickness. Consequently, in the condition with higher scene complexity, subjects perceived higher level of vection (reflected in the higher rated level of apparent self-motion ratings), which was in conflict with the stationary body movement perceived by the vestibular system. As a result, sickness occurred.

10.1.2 Discussion on the potential applications of the proposed 'Spatial Velocity' (SV) metric

10.1.2.1 Correlated relationships between 'Spatial Velocity' and rated levels of cybersickness

The proposed use of SV to quantify visual stimuli in a virtual environment is of great importance because it can be used to compare the results of different studies. For example, cybersickness studies involve different virtual reality simulations can use 'spatial velocity' as the independent variable and the nausea ratings or the sickness scores as the dependent variables. As a consequent, results of different studies can be directly compared. Of course, other factors such as field-of-view, stereoscopic presentation, gender of the subjects, will also affect the comparison. Nevertheless, this research represents the first step towards a universal metric to quantify visual stimuli responsible for the generation of cybersickness. Future research to include the effects of other factors are presented in Section 10.2. Example plots of 'Spatial Velocity' (SV) for the 3 experiments are shown in Figure 10.1 and Figure 10.2. Inspection of Figure 10.1 shows that total sickness severity scores increased with increasing SV in both fore-and-aft and yaw axes. This confirms that SV do influence the levels of cybersickness and can be used as a quantifying metric for virtual scene movement. The absence of significant effects in other axes could be due to the lack of SV in those axes. This explanation is strengthened by the results of Experiment one. Inspection of Figure 10.2 showed that an increase in SVs in pitch, yaw, and roll axes can also produce a corresponding increase in nausea ratings.

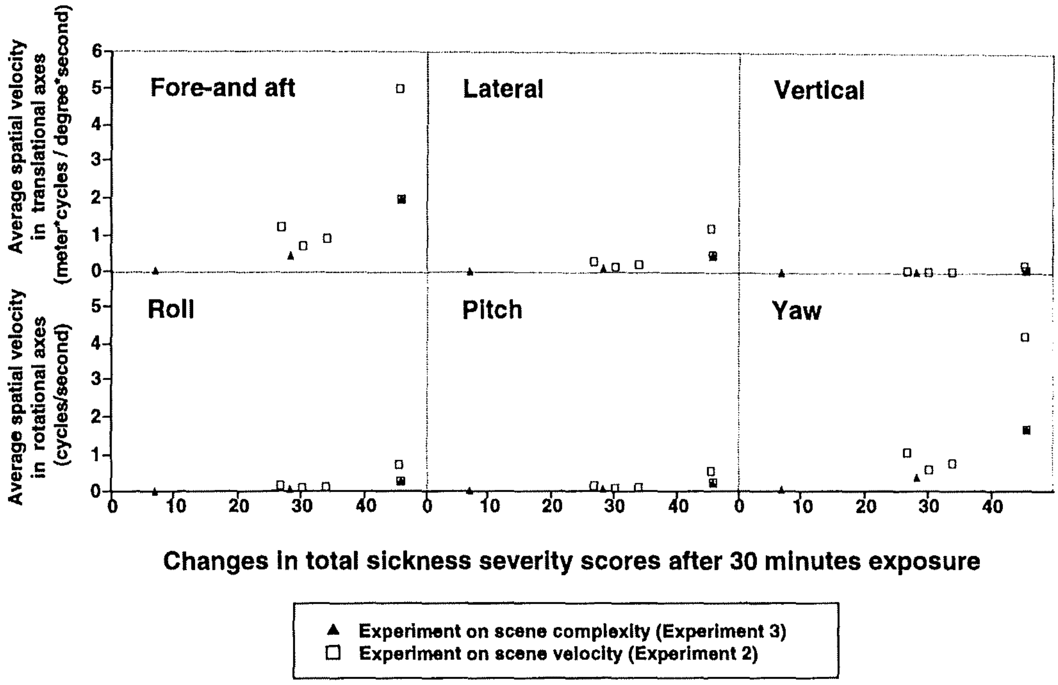


Figure 10.1 Increase in total sickness severity score after 30 minutes exposure of virtual simulation with different r.m.s. levels of 'spatial velocity' in the six axes.

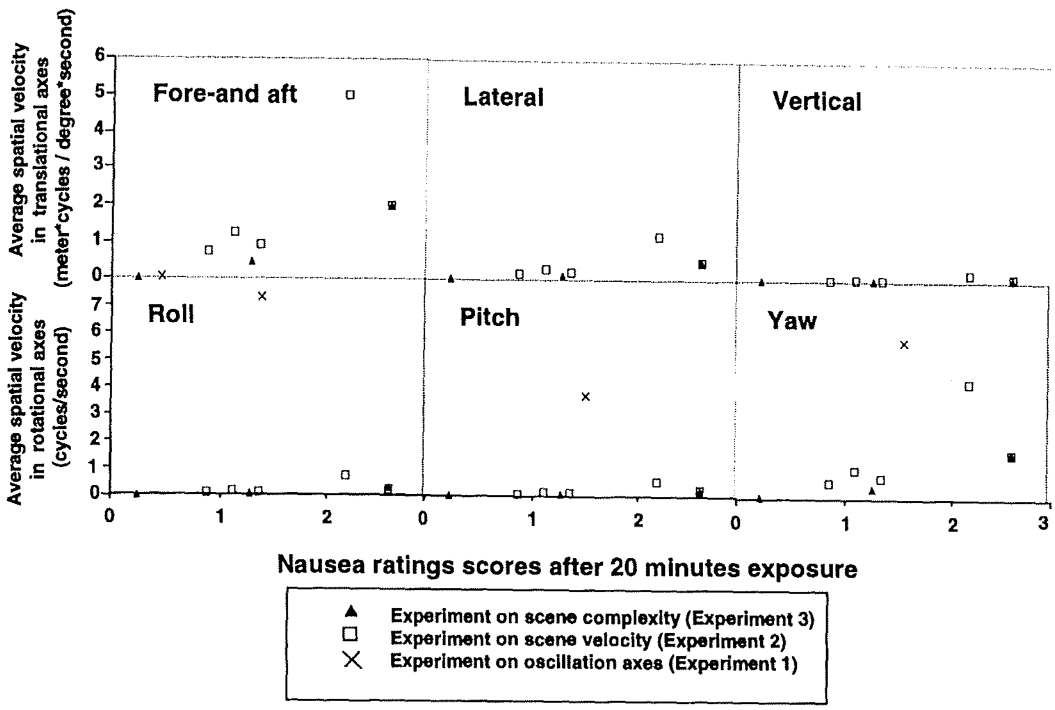


Figure 10.2 Increase in nausea ratings after 20 minutes exposure of virtual simulation with different r.m.s. levels of 'spatial velocity' in the six axes

10.1.2.2 Formulation of Cybersickness Dose Value (CSDV)

As noted by a review of literature, the British standard 6841 (BSI, 1987) defines a Motion Sickness Dose Value (MSDV) to predict level of seasickness. This MSDV uses a vibration stimulus measurement (i.e. vertical ship motion acceleration) to predict the percentage of passengers that will feel seasick after a given exposure to ship motion. The general form of MSDV is:

$$MSDV = [\int_0^T a^n(t)\,dt]^{1/n}$$

Where 'a' is the frequency weighted ship motion acceleration in vertical axis (unit: ms^{-2}), n is either 2 or 4, and T is the exposure period of ship motion in seconds. Griffin and Lawther (1988) reported that vomiting incidence and illness magnitude of seasickness were found to be significantly correlated to the root mean square magnitude of the vertical z-axis acceleration and duration of exposure.

In a virtual environment, visual stimuli have been identified to have significant influence on rated level of cybersickness. Since visual stimuli can be quantified by 'spatial velocity', so 'spatial velocity' can be treated as the basic unit to be accumulated within a dose value for predicting cybersickness. As a result, it is believed that the proposed quantitative metric ('spatial velocity') can contribute towards the formulation of a Cybersickness Dose Value (CSDV). A general form of CSDV is as follows:

$$CSDV = [\int_0^T SV^n(t)\,dt]^{1/n}$$

A dose is proposed to be a time integral of SV over the exposure period (T).

10.2 Limitations and future work

As this is the first step in proposing a metric to quantify visual stimuli for the study of cybersickness, there are some limitations in the proposed 'spatial velocity' metric and the proposed formulation of Cybersickness Dose Value. The limitations can be grouped into four categories: (i) the methods used to calculate 'spatial velocity'; (ii) display-related factors; (iii) task-related factors, and (iv) subject-related factors.

(I) The methods used to calculate 'spatial velocity'

In this study, the gray scale values of a captured scene were used in the calculation of 'spatial velocity'. Although previous literature has shown that color do not affect levels of vection-induced motion sickness, future studies to verify the effects of color and to include the influence of color in the 'SV' metric are desirable. Besides, 'spatial frequency' was used to quantify the complexity of the gray mapped scene. Explanations of the use of 'spatial frequency' instead of Michelson Contrast are presented in Chapter four. Future development work of the 'spatial velocity' measurements can include the uses of both colors and Michelson Contrast.

In addition, the number of snaps shots taken for a virtual environment simulation and the methods used in calculating the average dominant spatial frequency were arbitrarily chosen in this early stage of research. Further studies to determine the optimal algorithms are necessary.

(II) Display-related factors.

As mentioned in the review of literature, display's field-of-view and stereoscopic presentation have significant effects on levels of cybersickness. For example, Dizio and Lackner (1997) reported that reducing the display's field-of-view form 126° to 67° reduced the sickness rating by half. Enrlich (1997) reported that stereoscopic condition was more nauseogenic than biocular condition. This research used a field-of-view of 48° (horizontal) × 36° (vertical) and biocular presentation. For future research, it is appropriate to add weighting factors concerning display-related factors to the formulation of a CSDV.

(III) Task-related factors

Regan (1995) reported that, repeated-runs of virtual reality simulation with separation of less than one week could significantly decrease (not eliminate) the cybersickness level. Future work on Cybersickness Dose Value should include an additional weighting factor to account for the effects of repeated exposure. The results of all three experiments indicated that, beyond about 15 minutes, nausea ratings do not increase linearly with duration. Further investigation of the effects of longer duration of exposure is desirable.

(IV) Subject-related factors

Past studies showed that, females were more susceptible to simulator sickness (Kennedy *at al.*, 1995) and cybersickness (Regan and Price, 1993; Kolasinski, 1996; Rich and Braun, 1996). In addition, Stern (1993) reported that Chinese females were more susceptible to vection-induced motion sickness. Therefore, further investigation of the effects of human race and gender are desirable if a universal Cybersickness Dose Value (CSDV) is required. In view of the effects of short-term adaptation (i.e. effects of repeated-run with a separation of less than one week, as discussed in the last paragraph), a factor related to the level of training may be added to the CSDV. Further studies to confirm this are needed.

10.3 Conclusion

A 'spatial velocity' metric has been developed to measure and quantify the scene movement perceived by a user during a virtual reality simulation. 'Spatial velocity' consists of two components: (i) 'spatial frequency' to quantify scene complexity and (ii) velocity to quantify scene velocity relative to a user's viewpoint. Two experiments (Experiments two and three) have been conducted to study the effects of scene complexity and velocity (i.e. the two key components of 'spatial velocity') on levels of cybersickness and vection illusion. Data showed that sickness ratings increase with increasing 'spatial velocity' in yaw and fore-and-aft axes. This finding is important because it indicated that 'spatial velocity can be used as a predictive measure of cybersickness. The 'spatial velocity' metric is the first of its kind for quantifying visual stimuli in a virtual environment. This proposed 'spatial velocity' makes the formulation of a Cybersickness Dose Value (CSDV) possible. A simple form of CSDV using 'spatial velocity' as the basic unit has been presented and the use of 'spatial velocity' to establish a CSDV is also discussed.

With the proposed 'spatial velocity' metric, researchers within the field of cybersickness research can express the measured sickness as functions of 'spatial velocity'. This will facilitate direct comparisons of experimental results among different studies. Such comparisons will further the understanding on why virtual reality simulation will cause symptoms of cybersickness. With a CSDV, engineers can customize a virtual reality simulation system to reduce levels of cybersickness. The understanding of the shortcomings of virtual reality systems will enable their effective and appropriate uses in training simulation and multi-media applications. Furthermore, guidelines and safety standards base on a CSDV can be developed for virtual reality training systems.

References

Barfield, W., Rosenberg, C., and Kraft C. (1990). Relationship between scene complexity and perceptual performance for computer graphics simulations. Display, October 1990, pp. 179-85.

Bayarri, S., Fernandez, M. and Perez, M. (1996) Virtual reality for driving simulation. [Journal (J)] Commun. ACM (USA). Vol 39, No 5, pp. 72-6.

Bliss, J.P., Tidwell, P.D., and Guest, M.J. (1997) The effectiveness of virtual reality for administering spatial navigation training to firefighters. Presence, Vol. 6, No 1, February 1997, pp. 73-86.

Bliss, J.P., Tidwell, P.D., Loftin, R.B., Johnson, B.E., Lyde, C.L. and Weathinton, B. (in preparation) An experimental evaluation of virtual reality for training teamed navigation skills. Technical Report 96-01. Houston, TX: University of Houston Virtual Environment Technology Laboratory.

British Standards Institution (1987) Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock: BS6841. London: British Standards Institution.

Costello, P.J. and Howarth, P.A. (1996) The visual effects of immersion in four virtual environments. VISERG Internal Report 9604. Department of Human Sciences, Loughborough University, Leicestershire, LE11 3TU, United Kingdom.

DiZio, P. and Lackner, J.R. (1997) Circumventing side effects of immersive virtual environments. Proceeding of the 7th International Conference on Human-Computer Interaction, 24-29 August, San Francisco, CA.

Ehrlich, J.A. (1997) Simulator sickness and HMD configuration. Proceedings of SPIE, SPIE Vol. 3206, pp.170-178.

Finch, M. and Howarth, P.A. (1996) A comparison between two methods of controlling movement within a virtual environment. VISERG Internal report 9606. Department of Human Sciences, Loughborough University, Leicestershire, LE11 3TU, United Kingdom.

Griffin, M.J. (1990) Handbook of human vibration. Academics Press. ISBN 0-12-303040-4.

Harris, L. Jenkin, M., and Zikovitz, D.C. (1998) Vestibular cues and virtual environments. Proceedings. IEEE 1998 Virtual Reality Annual International Symposium. pp. 133-8.

Hettinger, L.T., Berbaum, K.S., Kennedy, R.S., Dunlap, W.P. and Nolan, M.D. (1990) Vection and simulator sickness. Military Psychology, 2(3), pp.171-181.

Howarth, P.A. and Costello, P.J. (1997) The occurrence of virtual simulation sickness symptoms when an HMD was used as a personal viewing system. Display, Vol. 18, No.2, pp. 107-116.

Hu, S., Davis, M.S., Klose, A.H., Zabinsky, E.M. Meux, S.P., Jacobson, H.A., Westfall, J.M. and Gruber, M.B. (1997) Effects of spatial frequency of a vertically striped rotating drum on vection-induced motion sickness. Aviation, Space, and Environment Medicine. Vol.68, No.4, April, pp306-311

Hu, S., Stern, R.M., Vasey, M.W., and Koch K.L. (1989) Motion sickness and gastric myoelectric activity as a function of speed of rotation of a circular vection drum. Aviation Space & Environmental Medicine. 1989; 60: 411-4

Hu, S., Stern, R.M. and Koch, K.:L. (1992) Electrical acustimulation relieves vection induced motion sickness. Gastroenterology 1992;102:1854-58.

Hu, S., Stritzel, R., Chandler, A., and Stem, R.M. P6 acupressure reduces symptoms of vection-induced motion sickness. Aviation Space & Environmental Medicine. 1995; 66:631-4.

Kennedy, R.S. and Stanney, K.M. (1997) Aftereffects of virtual environment exposure: psychometric issues. Proceeding of the 7th International conference on Human-Computer Interaction, 24-29 August, San Franciso, CA.

Kennedy, R.S., Fowlkes, J.E., Berbaum, K.S., and Lilienthal, M.G. (1992). Use of a motion sickness history questionnaire for prediction of simulator sickness. Aviation, Space, and Environmental Medicine, 63(7), 588-593.

Kennedy, R.S., Berhaum, K.S. and Smith, M.G. (1993a) Methods for correlating visual scene elements with simulator sickness incidence. Proceedings of the Human Factors and Ergonomics Socity 37th Annual conference, pp.1252-1256.

Kennedy, R.S., Lane, N.E., Berbaum, K.S. and Lilienthal, M.G. (1993b) Simulator Sickness Questionnaire (SSQ): a new method for quantifying simulator sickness. International Journal of Aviation Psychology, 3(3), pp.203-220.

Kennedy, R.S., Drexler, J.M. and Berbaum, K.S. (1994) Methodological and measurement issues for identification of engineering features contributing to virtual reality sickness. Proceedings of the IMAGE VII Conference, Tucson, Arizona 12-17 June 1994.

Kennedy, R.S., Lanham, D.S., Massey, C.J., Drexler, J.M., and Lilienthal, M.G. (1995). Gender differences in simulator sickness incidence: Implications for military virtual reality systems. Safe Journal, 25(1), pp.69-76.

Kennedy, R.S., Jones, M.B., Stanney, K.M., Ritter, A.D. and Drexler, J.M. (1996) Human factors safety testing for virtual environment mission-operation training. Final Report, Contract No. NAS9-19482. Houston, TX: NASA Johnson Space Center.

Kennedy, R.S., Lanham, S., Drexler, J.M., Massey, C.J. and Lilienthal, M.G. (1995) Cybersickness in several flight simulators and VR devices: a comparison of incidences, symptom profiles, measurement techniques and suggestions for research. Proceedings of the Conference of the FIVE Working Group. London, 18-19, Decemeber, 1995. pp, 243-251.

Kim, W. S. and Schenker P. (1992) A teleoperation training simulator with visual and kinesthetic force virtual reality. [Conference Paper (C)] Proc. SPIE - Int. Soc. Opt. Eng. (USA). Vol 1666, pp. 560-9

Kolasinski, E.M. (1995) Simulator sickness in virtual environments. United States Army Research Institute for the behavioral and social sciences. Technical Report 1027.

Kolasinski, E.M. (1996) Prediction of simulator sickness in a virtual environment. PhD thesis, Department of Psychology, University of Central Floride, Orlando, Florida (UMI Dissertation Service, USA).

Lackner, J.R., and Teixeira R.A. (1977) Optokinetic motion sickness: Continuous head movements attenuate the visual induction of apparent self-rotation and symptoms of motion sickness. Aviation Space & Environmental Medicine, 48(3): pp. 248-253.

Lawther, A. and Griffin, M.J. (1986) The motion of a ship at sea and the consequent motion sickness amongst passengers. [Journal Article] Ergonomics. 29(4):535-52, 1986 Apr.

Lawther, A. and Griffin, M.J. (1988) Motion sickness and motion characteristics of vessels at sea. [Journal Article] Ergonomics. Vol. 31, No. 10, 1373-94.

Lin, F., Hon, C.L. and Su, C.J. (1996) A virtual reality based training system for CNC milling machine operation. Annual journal of IIE(HK), pp.13-16.

McCauley, M.E. and Sharkey, T.J. (1992) Cybersickness: perception of self-motion in virtual environments. PRESENCE, 1(3), pp.311-318.

Muller, C.H., Wiest, G. and Deecks, L. (1990) Vertically moving visual stimuli and vertical vection - a tool against space motion sickness? Proceedings of the Fourth European Symposium on Life Sciences Research in Space, held in Trieste, Italy, from 28 may to June 1990 (ESA SP-307 November).

Muth, E.R., Jokerst, M., Stern, R.M., and Koch K.L. (1995) Effects of dimenhydrinate on gastric tachyarrhythmia and symptoms of vection-induced motion sickness. Aviation Space & Environmental Medicine. 1995; 66:1041-5

Previc, F.H., Varner, D.C. and Gillingham, K.K (1992) Visual scene effects on the somatogravic illusion. Aviation, Space, and Environmental Medicine, December, pp. 1060-1063.

Reason, J.T. and Brand, J.J. (1975). Motion sickness. London: Academic Press.

Regan, C (1995) An investigation into nausea and other side-effects of head-coupled immersive virtual reality. Virtual Reality, 1 (1), pp.17-32.

Regan, E.C. and Price, K.R. (1993a) Some side-effects of immersion virtual reality. APRE, UKMOD. Report 93RO10.

Regan, E.C. and Price, K.R. (1993b) Subjective views on an immersion virtual reality system and its peripherals. Working paper 16/93. UKMOD.

Regan, E.C. and Price K.R. (1993c) Some side-effects of immersion virtual reality: the effects of increasing head movements, rapid interaction, and seating subjects. APRE, UKMOD, Report 93RO22.

Rich, C.J. and Braun, C.C. (1996) Assessing the impact of control and sensory compatibility on sickness in virtual environments. Proceedings of Human Factors and Ergonomics Society 40th Annual Meeting, Santa Monica, CA: Human Factors & Ergonomics Society. Pp. 1122-1125.

Satava, R.M., and Jones S.B. (1997) Virtual environments for medical training and education. Presence, Vol. 6. No. 2, April 1997, pp. 139-146.

Sharkey, T.J., and McCauley, M.E. (1991). The effect of global visual flow on simulator sickness. Proceedings of the AIAA/AHS Flight Simulation Technologies Conference (pp.496-504). (Report No. AIAA-91-2975-CP.) Washington, D.C. : American Institute of Aeronautics and Astronautics.

Stanney, K.M. and Kennedy, R.S. (1997) Development and testing of a measure of the kinesthetic position sense used to assess the aftereffects from virtual environment exposure. Proceedings of IEEE 1997 Virtual Reality Annual International Symposium, pp.87-94.

Stern, R.M., Hu, S., LeBlanc, R., and Koch K.L. (1993) Chinese hyper-susceptibility to vection-induced motion sickness. Aviation Space & Environmental Medicine. 64(9 Pt 1):827-30, 1993 Sep.

Stern, R.M., Hu, S.Q. Vasey, M.W., and Koch K.L. (1989) Adaptation to vection-induced symptoms of motion sickness. Aviation Space & Environmental Medicine. 60(6):566-72,1989 Jun.

Stern, R.M., Uijtdehaage S.H.J., Muth, E.R., Koch, K.L. Effects of phenytoin on vection-induced motion sickness and gastric myoelectric activity. Aviation Space & Environmental Medicine. 1994; 65:518-21

So, R.H.Y. (1994). An investigation of the effects of lags on motion sickness with a head-coupled visual display. Proc. of the UK Informal Group Meeting on Human Response to Vibration held at the Institute of Naval Medicine, Alverstoke, UK, 19th-21st, September, 1994.

Wilson, J.R., Nichols, S. and Haldane, C. (1997) Presence and side effects: complementary or contradictory? Proceedings of the 7th International Conference on Human-Computer Interaction, San Franciso, August, pp.889-892.

Woodman, P.D., Griffin, M.J. (1997) Effects of direction of head movement on motion sickness caused by coriolis stimulation. Aviation Space & Environmental Medicine, 1997; 68: pp.93-98.

Yang, T.D. and Pei, J.S. (1991) Motion sickness severity under interaction of vection and head movements. [Journal Article] Aviation Space & Environmental Medicine. 62(2):pp.141-4

Appendix A

This appendix is a motion sickness history question to ask the subjects' motion sickness experience. Chapter 7 (Effects of scene rotation axes on cybersickness with a head-coupled virtual reality system (Experiment 1)) of the thesis is related to this appendix.

PREVIOUS SICKNESS EXPERIENCE
confidential

Instructions: please fill in this questionnaire. Circle below the answer which most closely corresponds to your own experiences. However, feel free to add any comments you would like to make at the end of the questionnaire.

1. In the past 12 months how many times have you travelled as a passenger in the following modes of transport?

Taxi	Never	1	2-4	5-16	17-64	65-256	257 or more
Buses/Coaches	Never	1	2-4	5-16	17-64	65-256	257 or more
Small boats	Never	1	2-4	5-16	17-64	65-256	257 or more
Ferry	Never	1	2-4	5-16	17-64	65-256	257 or more
Aeroplanes	Never	1	2-4	5-16	17-64	65-256	257 or more
Trains/MTR	Never	1	2-4	5-16	17-64	65-256	257 or more
other - specify ____________	Never	1	2-4	5-16	17-64	65-256	257 or more

2. In the past 12 months how many times have you felt ill whilst travelling as a passenger on the following types of transport?

Taxi	Never	1	2	3-4	5-8	9-16	17 or more
Buses/Coaches	Never	1	2	3-4	5-8	9-16	17 or more
Small boats	Never	1	2	3-4	5-8	9-16	17 or more
Ferry	Never	1	2	3-4	5-8	9-16	17 or more
Aeroplanes	Never	1	2	3-4	5-8	9-16	17 or more
Trains/MTR	Never	1	2	3-4	5-8	9-16	17 or more
other - specify ____________	Never	1	2	3-4	5-8	9-16	17 or more

3. In the last 12 months how many times have you vomited whilst travelling as a passenger on the following types of transport?

Taxi	Never	1	2-4	5-16	17-64	65-256	257 or more
Buses/Coaches	Never	1	2-4	5-16	17-64	65-256	257 or more
Small boats	Never	1	2-4	5-16	17-64	65-256	257 or more
Ferry	Never	1	2-4	5-16	17-64	65-256	257 or more
Aeroplanes	Never	1	2-4	5-16	17-64	65-256	257 or more
Trains/MTR	Never	1	2-4	5-16	17-64	65-256	257 or more
other - specify ____________	Never	1	2-4	5-16	17-64	65-256	257 or more

4. Have you ever vomited on the following types of transport?

Cars	Yes	No	Can't remember
Buses/Coaches Y	Yes	No	Can't remember
Small boats	Yes	No	Can't remember
Ferry	Yes	No	Can't remember
Aeroplanes	Yes	No	Can't remember
Trains/MTR	Yes	No	Can't remember
other - specify ____________	Yes	No	Can't remember

5. Would you avoid any of the following types of transport because of motion sickness?

Cars	Never	Occasionally	Often	Always
Buses/Coaches	Never	Occasionally	Often	Always
Small boats	Never	Occasionally	Often	Always
Ferry	Never	Occasionally	Often	Always
Aeroplanes	Never	Occasionally	Often	Always
Trains/MTR	Never	Occasionally	Often	Always
other - specify ____________	Never	Occasionally	Often	Always

6. Which of the following best indicates your susceptibility to motion sickness relative to others of the same age? **(higher susceptibility means that you are more likely to feel motion sickness)**

a) As a child (up to the age of 12)

Much less than average	less than average	Average	More than average	Much more than average

b) at your present age

Much less than average	less than average	Average	More than average	Much more than average

7. In your life how many times have you suffered from travel sickness (air, sea and land transport) ?

Never 1 2-4 5-16 17-64 65-256 257 or more

8. IIn the past 12 months, how many times have you played computer games?

Never 1 2-4 5-16 17-64 65-256 257 or more

9. In the past 12 months, how many times have you played a video game in an arcade?

Never 1 2-4 5-16 17-64 65-256 257 or more

10. In the past 12 months, how many times have you been on a fair ground motion simulator? (e.g. those in the Ocean Park)

Never 1 2-4 5-16 17-64 65-256 257 or more

Appendix B

This appendix is a symptom checklist containing 27 items (adapted from Kennedy *et al.*, 1993) which is used to measure symptoms. Chapter 7(Effects of scene rotation axes on cybersickness with a head-coupled virtual reality system (Experiment 1)), Chapter 8 (Studies of effects of scene velocity on cybersickness with a head-coupled virtual reality system (Experiment 2)), and Chapter 9 (Studies of effects of scene complexity on cybersickness with a head-coupled virtual reality system (Experiment 3)) are related to this appendix.

SYMPTOM CHECKLIST

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 simulation minutes exposure.

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

*1.	General discomfort	None	Slight	Moderate	Severe
*2.	Fatigue	None	Slight	Moderate	Severe
3.	Boredom	None	Slight	Moderate	Severe
4.	Drowsiness	None	Slight	Moderate	Severe
*5.	Headache	None	Slight	Moderate	Severe
*6.	Eyestrain	None	Slight	Moderate	Severe
*7.	Difficulty focusing	None	Slight	Moderate	Severe
*8.	Salivation increase	None	Slight	Moderate	Severe
9.	Salivation decrease	None	Slight	Moderate	Severe
*10.	Sweating	None	Slight	Moderate	Severe
*11.	Nausea	None	Slight	Moderate	Severe
*11.	Difficulty concentrating	None	Slight	Moderate	Severe
12.	Mental depression		No	Yes	
*13.	Fullness of the head"		No	Yes	
*14.	Blurred vision		No	Yes	
*15.	Dizziness eyes open		No	Yes	
*16.	Dizziness eyes close		No	Yes	
*17.	Vertigo		No	Yes	
18.	Visual flashbacks*		No	Yes	
19.	Faintness		No	Yes	
20.	Aware of breathing		No	Yes	
21.	Stomach awareness		No	Yes	
22.	Loss of appetite		No	Yes	
23.	Increased appetite		No	Yes	
24.	Desire to move bowels		No	Yes	
25.	Confusion		No	Yes	
*26.	Burping		No	Yes	
*27.	Vomiting		No	Yes	
28.	Other		No	Yes	

Appendix C

This appendix is a seven-point nausea rating scale used to measure the level of nausea ratings during the experiment (adapted from Golding and Kerguelen, 1992) Chapter 7(Effects of scene rotation axes on cybersickness with a head-coupled virtual reality system (Experiment 1)), Chapter 8 (Studies of effects of scene velocity on cybersickness with a head-coupled virtual reality system (Experiment 2)), and Chapter 9 (Studies of effects of scene complexity on cybersickness with a head-coupled virtual reality system (Experiment 3)) are related to this appendix.

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 D

This appendix is a simulation assessment form used to measure the level of realism of the virtual reality simulation (modified form Regan, 1995). Chapter 7(Effects of scene rotation axes on cybersickness with a head-coupled virtual reality system (Experiment 1)), Chapter 8 (Studies of effects of scene velocity on cybersickness with a head-coupled virtual reality system (Experiment 2)), and Chapter 9 (Studies of effects of scene complexity on cybersickness with a head-coupled virtual reality system (Experiment 3)) are related to this appendix.

SIMULATION ASSESSMENT

confidential

Instructions: please fill in this questionnaire about your experience with the -coupled simulation. Circle appropriate for each question.

1. During the simulation, did you feel that you were moving?

   Totally A lot Somewhat A little Not at all

2. How uncomfortable was the head-mounted display?

   Totally A lot Somewhat A little Not at all

3. How completely did you believe you were part of the virtual environment?

   Totally A lot Somewhat A little Not at all

4. How flat and missing in depth did the world appear?

   Totally A lot Somewhat A little Not at all

5. How excited do you feel after the experience?

   Totally A lot Somewhat A little Not at all

6. How real was the graphics simulation?

   Totally A lot Somewhat A little Not at all

7. Any remarks?

Appendix E

This appendix illustrates the computation method to calculate the simulation sickness score (Nausea sub-score, Oculomotor sub-score, Disorientation sub-score and the Total Sickness severity, adapted form Kennedy *et al.*, 1993). Chapter 7(Effects of scene rotation axes on cybersickness with a head-coupled virtual reality system (Experiment 1)), Chapter 8 (Studies of effects of scene velocity on cybersickness with a head-coupled virtual reality system (Experiment 2)), and Chapter 9 (Studies of effects of scene complexity on cybersickness with a head-coupled virtual reality system (Experiment 3)) are related to this appendix.

Computation of SSQ Scores

Symptoms (Scored 0,1,2,3)	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

$N = [1] \times 9.54$

$O = [2] \times 7.58$

$D = [3] \times 13.92$

$TS = ([1] + [2] + [3]) \times 3.74$

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

Appendix F

This appendix illustrates the statistical results of Experiment one. Chapter 7 (Studies of effects of scene rotation axes on cybersickness with a head-coupled virtual reality system) is related to this appendix.

Table F.1 ANOVA result for nausea ratings (between with and without scene movement conditions)

Source	DF	SS	Mean Square	F Value	Pr > F
CONDS	1	34.1260417	34.1260417	107.88	0.0001*
MINUTES	4	67.3437500	16.8359375	53.22	0.0001*
CONDS*MINUTES	4	9.8895833	2.4723958	7.82	0.0001*
Error	310	98.062500	0.316331		

(Note that * indicate a significant effect at p=0.05)

Table F.2 SNK test on the effect of scene movement on nausea

SNK Grouping	Mean	N	scene movement
A	0.95417	240	with
B	0.20000	80	without

(Note that means with the same letter are not significantly different)

Table F.3 ANOVA result for nausea (duration effect on nausea ratings in the with scene movement condition)

Source	DF	SS	Mean Square	F Value	Pr > F
LEVELS	2	0.5583333	0.2791667	0.75	0.4733
MINUTES	4	74.8083333	18.7020833	50.28	0.0001*
LEVELS*MINUTES	8	1.4416667	0.1802083	0.48	0.8666
Error	225	83.6875000	0.3719444		

(Note that * indicate a significant effect at p=0.05)

Table F.4 SNK test on the effect of duration on nausea ratings in the with scene movement condition

SNK Grouping	Mean	N	MINUTES
A	1.5417	48	20
A			
A	1.3958	48	15
B	1.1458	48	10
C	0.6875	48	5
D	0.0000	48	0

(Note that means with the same letter are not significantly different)

Table F.5 ANOVA result for nausea (duration effect on nausea ratings in the without scene movement condition)

Source	DF	SS	Mean Square	F Value	Pr > F
LEVELS	0	0.00000000	.	.	.
MINUTES	4	2.42500000	0.60625000	3.67	0.0087*
LEVELS*MINUTES	0	0.00000000	.	.	.
Error	75	12.37500000	0.16500000		

(Note that * indicate a significant effect at p=0.05)

Table F.6 SNK test on the effect of duration on nausea ratings in the without scene movement condition

SNK Grouping		Mean	N	MINUTES
	A	0.4375	16	20
	A			
B	A	0.3125	16	15
B	A			
B	A	0.2500	16	10
B				
B		0.0000	16	5
B				
B		0.0000	16	0

(Note that means with the same letter are not significantly different)

Table F.7 ANOVA for nausea ratings (comparison between with and without scene movement conditions at each five minutes interval),

At 5 minutes interval					
Source	DF	SS	Mean Square	F Value	Pr > F
CONDS	1	5.67187500	5.67187500	28.56	0.0001*
Error	62	12.31250000	0.19858871		
At 10 minutes interval					
Source	DF	SS	Mean Square	F Value	Pr > F
CONDS	1	9.63020833	9.63020833	28.46	0.0001*
Error	62	20.97916667	0.33837366		
At 15 minutes interval					
Source	DF	SS	Mean Square	F Value	Pr > F
CONDS	1	14.0833333	14.0833333	35.04	0.0001*
Error	62	24.9166667	0.4018817		
At 20 minutes interval					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	14.6302083	14.6302083	22.76	0.0001*
Error	62	39.8541667	0.6428091		

(Note that * indicate a significant effect at p=0.05)

Table F.8 SNK test for nausea ratings (comparison between with and without scene movement conditions at each five minutes interval)

SNK Grouping	Mean	N	CONDS
At 5 minutes interval			
A	0.6875	48	with
B	0.0000	16	without
At 10 minutes interval			
A	1.1458	48	with
B	0.2500	16	without
At 15 minutes interval			
A	1.3958	48	with
B	0.3125	16	without
At 20 minutes interval			
A	1.5417	48	with
B	0.4375	16	without

(Note that means with the same letter are not significantly different)

Table F.9 The descriptive statistics of the pre, post and change sickness score (Nausea, Oculomotor)

	Nausea	Sub-score	
Level	Time	N	Mean
Pitch	After	16	16.695
Pitch	Before	16	1.1925
Pitch	Change	16	15.503
Roll	After	16	27.4275
Roll	Before	16	3.5775
Roll	Change	16	23.85
Yaw	After	16	22.06125
Yaw	Before	16	5.36625
Yaw	Change	16	16.695
without	After	16	7.155
without	Before	16	2.385
without	Change	16	4.77
	Oculomotor	subscale	
Level	Time	N	Mean
Pitch	After	16	35.0575
Pitch	Before	16	7.58
Pitch	Change	16	27.478
Roll	After	16	41.21625
Roll	Before	16	9.475
Roll	Change	16	31.741
Yaw	After	16	37.9
Yaw	Before	16	6.6325
Yaw	Change	16	31.268
without	After	16	19.42375
without	Before	16	5.685
without	Change	16	13.7386

Table F.9 The descriptive statistics of the pre, post and change sickness score (Disorientation, Total sickness score)

	Disorientation	subscale	
Level	Time	N	Mean
Pitch	After	16	26.1
Pitch	Before	16	0
Pitch	Change	16	26.1
Roll	After	16	31.32
Roll	Before	16	1.74
Roll	Change	16	29.58
Yaw	After	16	30.45
Yaw	Before	16	2.61
Yaw	Change	16	27.84
without	After	16	7.83
without	Before	16	0
without	Change	16	7.83
	Total Sickness	Score	
Level	Time	N	Mean
Pitch	After	16	30.855
Pitch	Before	16	4.2075
Pitch	Change	16	26.648
Roll	After	16	39.50375
Roll	Before	16	6.545
Roll	Change	16	32.959
Yaw	After	16	35.53
Yaw	Before	16	6.0775
Yaw	Change	16	29.453
without	After	16	14.4925
without	Before	16	3.74
without	Change	16	10.7525

Table F.10. ANOVA result on Nausea sub-score of pre immersion profiles

Source	DF	SS	Mean Square	F Value	Pr > F
LEVELS	3	152.160019	50.720006	1.49	0.2263
Error	60	2042.072775	34.034546		

Table F.11. ANOVA result on Oculomotor sub-score of pre immersion profiles

Source	DF	SS	Mean Square	F Value	Pr > F
LEVELS	3	125.685875	41.895292	0.46	0.7134
Error	60	5501.450300	91.690838		

Table F.12. ANOVA result on Disorientation sub-score of pre immersion profiles, (degree of freedom of error is 60)

Source	DF	SS	Mean Square	F Value	Pr > F
LEVELS	3	81.7452000	27.2484000	1.36	0.2625
Error	60	1198.9296000	19.9821600		

Table F.13. ANOVA result on Total Sickness score of pre immersion profiles, (degree of freedom of error is 60)

Source	DF	SS	Mean Square	F Value	Pr > F
LEVELS	3	90.9194000	30.3064667	0.66	0.5789
Error	60	2748.5634000	45.8093900		

Table F.14. ANOVA result on Nausea sub-score (comparison between pre and post- immersion profiles of each condition individually)

Scene movement in pitch axis (					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	1922.62005	1922.62005	16.35	0.0003*
Error	30	3526.69950	117.55665		
Scene movement in yaw axis					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	2229.78420	2229.78420	9.50	0.0044*
Error	30	7042.02255	234.73409		
Scene movement in roll axis					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	4550.58000	4550.58000	13.70	0.0009*
Error	30	9965.77020	332.19234		
No scene movement					
Source	DF	SS	Mean Square	F Value	Pr > F
TIME	1	182.023200	182.023200	4.29	0.0471*
Error	30	1274.162400	42.472080		

(Note that * indicate a significant effect at p=0.05)

Table F.15. ANOVA result on Oculomotor sub-score (comparison between pre and post- immersion profiles)

Scene movement in pitch axis (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	6040.10405	6040.10405	15.04	0.0005*
Error	30	12051.47990	401.71600		
Scene movement in yaw axis (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	7821.25245	7821.25245	17.47	0.0002*
Error	30	13430.43350	447.68112		
Scene movement in roll axis (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	8060.05561	8060.05561	23.00	0.0001*
Error	30	10510.93018	350.36434		
No scene movement (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	1510.02601	1510.02601	9.99	0.0036*
Error	30	4535.46457	151.18215		

(Note that * indicate a significant effect at p=0.05)

Table F.16. ANOVA result on Disorientation sub-score (comparison between pre and post- immersion profiles)

Scene movement in pitch axis (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	5449.68000	5449.68000	10.85	0.0025*
Error	30	15065.33760	502.17792		
Scene movement in yaw axis (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	6200.52480	6200.52480	11.31	0.0021*
Error	30	16445.92320	548.19744		
Scene movement in roll axis (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	6999.81120	6999.81120	20.55	0.0001*
Error	30	10221.17760	340.70592		
No scene movement (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	490.471200	490.471200	7.64	0.0097*
Error	30	1925.553600	64.185120		

(Note that * indicate a significant effect at p=0.05)

Table F.17. ANOVA result on Total Sickness score (comparison between pre and post- immersion profiles)

Scene movement in pitch axis (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	5680.71405	5680.71405	16.90	0.0003*
Error	30	10081.56270	336.05209		
Scene movement in yaw axis (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	6939.59805	6939.59805	15.67	0.0004*
Error	30	13284.72310	442.82410		
Scene movement in roll axis (degree of freedom of error is 30)					
Source	DF	Squares	Square	F Value	Pr > F
Model	1	8690.23361	8690.23361	24.11	0.0001*
Error	30	10811.54057	360.38469		
No scene movement (degree of freedom of error is 30)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	924.930050	924.930050	9.64	0.0041*
Error	30	2877.948700	95.931623		

(Note that * indicate a significant effect at p=0.05)

Table F.18 ANOVA result for three subscales and total sickness score between with and without scene movement conditions

Nausea subscale					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	2322.69188	2322.69188	7.00	0.0103*
Error	62	20561.03730	331.62963		
Oculomotor subscale					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	3236.71053	3236.71053	7.74	0.0072*
Error	62	25936.77657	418.33511		
Disorientation subscale					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	4804.80120	4804.80120	6.93	0.0107*
Error	62	43004.03040	693.61339		
Total sickness score					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	4301.84267	4301.84267	8.83	0.0042*
Error	62	30193.10882	486.98563		

(Note that * indicate a significant effect at p=0.05)

Table F.19 SNK test on the effect of scene movement on the three subscale and the total sickness score (result between with and without scene movement)

Nausea subscale			
SNK Grouping	Mean	N	CONDS
A	18.683	48	with
B	4.770	16	without
Oculomotor subscale			
SNK Grouping	Mean	N	CONDS
A	30.162	48	with
B	13.739	16	without
Disorientation subscale			
SNK Grouping	Mean	N	CONDS
A	27.840	48	with
B	7.830	16	without
Total Sickness score			
SNK Grouping	Mean	N	CONDS
A	29.686	48	with
B	10.752	16	without

(Note that means with the same letter are not significantly different)

Table F.20 ANOVA result for nausea ratings (among scene oscillation in pitch, yaw and roll axes)

Source	DF	SS	Mean Square	F Value	Pr > F
LEVELS	2	0.5583333	0.2791667	0.75	0.4733
MINUTES	4	74.8083333	18.7020833	50.28	0.0001*
LEVELS*MINUTES	8	1.4416667	0.1802083	0.48	0.8666
Error	225	83.6875000	0.3719444		

(Note that * indicate a significant effect at p=0.05)

Table F.21 ANOVA result for duration effect on nausea ratings of each scene oscillation condition (pitch, yaw and roll)

Scene oscillation in pitch axis					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	4	27.6250000	6.9062500	21.25	0.0001*
Error	75	24.3750000	0.3250000		
Scene oscillation in yaw axis					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	4	24.5500000	6.1375000	23.68	0.0001*
Error	75	19.4375000	0.2591667		
Scene oscillation in roll axis					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	4	24.0750000	6.0187500	11.32	0.0001*
Error	75	39.8750000	0.5316667		

Table F.22 SNK test result for duration effect on nausea ratings of each scene oscillations condition (pitch, yaw and roll)

SNK Grouping		Mean	N	MINUTES
Scene oscillation in pitch axis				
	A	1.5625	16	20
	A			
	A	1.5000	16	15
	A			
	A	1.2500	16	10
	B	0.6875	16	5
	C	0.0000	16	0
Scene oscillation in yaw axis				
	A	1.6250	16	20
	B	1.2500	16	15
	B			
C	B	0.9375	16	10
C				
C		0.6250	16	5
	D	0.0000	16	0
Scene oscillation in roll axis				
	A	1.4375	16	20
	A			
	A	1.4375	16	15
	A			
B	A	1.2500	16	10
B				
B		0.7500	16	5
	C	0.0000	16	0

(Note that means with the same letter are not significantly different)

Table F.23 SNK test result of duration effect on nausea ratings among scene oscillation in pitch, yaw and roll oscillation

SNK Grouping	Mean	N	MINUTES
A	1.5417	48	20
A			
A	1.3958	48	15
B	1.1458	48	10
C	0.6875	48	5
D	0.0000	48	0

(Note that means with the same letter are not significantly different)

Table F.24 ANOVA result for Nausea, Oculomotor, Disorientation sub-scores and the Total Sickness score of the change sickness profiles in the three scene oscillations conditions.

Nausea subscale					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	2	652.249800	326.124900	0.76	0.4745
Error	45	19362.717900	430.282620		
Oculomotor subscale					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	2	174.763217	87.381608	0.17	0.8454
Error	45	23323.707375	518.304608		
Disorientation subscale					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	2	96.8832000	48.4416000	0.05	0.9483
Error	45	40981.593600	910.7020800		
Total Sickness score					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	2	319.966350	159.983175	0.26	0.7752
Error	45	28114.201775	624.760039		

Table F.25 ANOVA result for Q1 to Q6 of simulation assessment question

Q1: Did you feel you were moving during the experiment?					
Source	DF	SS	Mean Square	F Value	Pr > F
CONDS	1	19.3802083	19.3802083	55.94	0.0001*
Error	62	21.4791667	0.3464382		
Q2: How uncomforted of HMD?					
Source	DF	SS	Mean Square	F Value	Pr > F
CONDS	1	3.00000000	3.00000000	4.13	0.0463
Error	62	45.00000000	0.72580645		
Q3: How completely did you believe you were part of virtual environment?					
Source	DF	SS	Mean Square	F Value	Pr > F
CONDS	1	0.63020833	0.63020833	1.48	0.2291
Error	62	26.47916667	0.42708333		
Q4: How flat and missing in depth did the world appear?					
Source	DF	SS	Mean Square	F Value	Pr > F
CONDS	1	0.33333333	0.33333333	0.62	0.4346
Error	62	33.41666667	0.53897849		
Q5: How excited do you feel after the experiment?					
Source	DF	SS	Mean Square	F Value	Pr > F
CONDS	1	1.02083333	1.02083333	2.19	0.1441
Error	62	28.91666667	0.46639785		
Q6: How real was the graph simulation?					
Source	DF	SS	Mean Square	F Value	Pr > F
CONDS	1	0.18750000	0.18750000	0.32	0.5732
Error	62	36.25000000	0.58467742		

(Note that * indicate a significant effect at p=0.05)

Appendix G

This appendix illustrates the steps to capture a still picture in an Onyx workstation. Chapter 4(Method to quantify scene content in virtual environment) of the thesis is related to this appendix.

Steps to capture a picture in an Onyx workstation

1. Place the mouse pointer over the option 'Desktop' and then press the left button. A toolbox containing the ' Unix cell' option will automatically appear.

2. Place the mouse pointer over the 'Unix cell' option and then press the left button. A new Unix cell will automatically appear.

3. Type the command 'snapshot' in the Unix cell. A command button control with the name 'snapshot' will appear.

4. Move the virtual environment windows, so that the upper left corner of the picture just coincides with the lower right corner of the snapshot command button. (Remark: Not the upper left corner of the windows, since we just want to capture the picture without the border of the display window)

5. Move the mouse pointer to the lower right corner of the snapshot command button, the mouse pointer will automatically change into a camera icon. Press and hold the left button and move the mouse to the lower right corner of the picture. Release the mouse, a red line will just surround the edges of the picture.

6. Place the mouse pointer over the snapshot command button and then press left button, another toolbox will automatically appear beside the snapshot command button. Move the mouse to the 'New filename' option and press the left button. A textbox will appear, type the name with extension 'rgb' (e.g. figure.rgb) and then press 'Enter'.

7. Place the mouse pointer over the snapshot command button again and press the left button. Move the mouse pointer over the 'save & exit' option and then press the left button.

8. Now the particular view of the virtual environment is captured with file name figure.rgb in the current working directory.

Appendix H

This appendix illustrates the steps to store a picture in portable graymap file format 'pgm' in an Onyx workstation. Chapter 4 (Method to quantify scene content in virtual environment) is related to this appendix.

Steps to store a picture in 'pgm' format in an Onyx workstation

1. Place the mouse pointer over the 'Desktop option' and press the left button. A toolbox containing the 'Unix cell' will automatically appear.

2. Place the mouse pointer over the 'Unix cell' option and press the left button. A new Unix cell will automatically appear.

3. Type the command 'xv' in the Unix cell. A window with the name of the picture browser 'XV' exists. 'XV' is developed by John Broadley.

4. Move the mouse pointer over the 'XV' window and press left button. A 'XV control' form will automatically appear.

5. Place the mouse pointer over the 'load' command button and press left button of the mouse, a 'XV load' form will appear. Then choose the file you want to browser (e.g. figure.rgb). After you have chosen the picture to browser, the picture will automatically appear.

6. Move the mouse pointer to the 'XV' control form and then press the 'save' command button. A 'XV save' form will appear. Inside the "XV save' form, turn on the 'PBM (ascii)' radio button (which is in the Format option) and then choose the 'Greyscale' radio button (which is inside the Color option). Now the textbox of the save file name will show the filename of the picture with extension 'pgm' (e.g. figure.pgm). Press the 'OK' button. A new file (e.g. figure.pgm) is saved in the current working directory.

7. You can move the mouse pointer over the 'XV control' form again and then press the 'TextView' command to view the gray scale of each pixel of the picture, which is stored in 'pgm' format.

Appendix I

The appendix illustrates the program code used to extract the gray scales of the pixels of a picture (necessary for the calculation of spatial frequencies of the picture). Chapter 4 (Method to quantify scene content in virtual environment) of the thesis is related to this appendix.

C++ programming code use to extract gray scale of a picture

```
#include <iostream.h>
#include <fstream.h>
#include <string.h>
#include <malloc.h>
#include <stdlib.h>
#include <stdio.h>
#include <math.h>

char *inputfile = new char[256];
char *outputfile = new char[256];
char *inputline = new char[256];
int coll[150];
int count_coll;
int in_count;
int out_count;
float mt, rt;
int mtget;

void
main()
{
        int filename;
        int width, height;
        char *c=new char[10];
        int i, j, k;
        int count;
        int temp;

        cout << "Please input the file name:";
        cin >> inputfile;
        cout << "\n";

        count = 0;

        ifstream infile(inputfile, ios::in);
```

```
infile.getline(inputline, 150);
infile.getline(inputline, 150);
infile.getline(inputline, 150);
c = strtok(inputline," ");
width = atoi(c);
c = strtok(NULL," ");
height = atoi(c);
infile.getline(inputline, 150);

// Put all of the tokens into a file "all"
sprintf(outputfile, "all");
ofstream oFile(outputfile, ios::out);

while (infile.getline(inputline, 150)) {
        c = strtok(inputline, " ");
        oFile << c << "\n";
        while (c = strtok(NULL, " ")) {
                oFile << c << "\n";
        };
};
oFile.close();
infile.close();

sprintf(inputfile, "all");
ifstream infile1(inputfile, ios::in);

cout << "Transforming ";

// Write the widht files " w1, w2,....."
for (j=1;j<=height;j++) {
        count = 0;
        sprintf(outputfile, "w%d", j);
        ofstream oFile(outputfile, ios::out);
        while (count < width) {
                count++;
                infile1.getline(inputline,150);
                cout << ".";
                c = strtok(inputline, "\0");
                oFile << c << "\n";
        };
        oFile << "\n";
        oFile.close();
};
infile1.close();

// Write the height files " h1, h2,....."
```

```
	for (j=1;j<=width;j++) {
		sprintf(inputfile, "all");
		ifstream infile(inputfile, ios::in);

		cout << ".";
		sprintf(outputfile, "h%d", j);
		ofstream oFile(outputfile, ios::out);

		for (i=1; i <= j; i++) {
			infile.getline(inputline, 150);
		};
		c = strtok(inputline, "\0");
		oFile << c << "\n";

		for (i=1; i < height; i++) {
			for (k=1; k <= width; k++) {
				infile.getline(inputline,150);
			};
			c = strtok(inputline, "\0");
			oFile << c << "\n";
		};
		oFile << "\n";
		oFile.close();
		infile.close();
	};
	cout << "\n";
}
```

Appendix J

This appendix illustrates the program code of a MATLAB file that is used to calculate the spatial frequencies of a picture. Chapter 4(Method to quantify scene content in virtual environment) of the thesis is related to this appendix.

Program code of MATLAB to calculate the spatial frequencies of a picture

```
%h_resol is the original horizontal resolution of the bitmap
        [pixels]
%v_resol is the original vertical resolution of the bitmap
        [pixels]
%h_FOV is the original horizontal FOV of the display apparature (VR4)
        [degrees]
%v_FOV is the original vertical FOV of the display apparature (VR4)
        [degrees]
%h_sr is the original horizontal sampling rate
[sample(s)/degree]
%v_sr is  the original vertical sampling rate
[sample(s)/degree]
%SF_h is an array, which store the average spatial frequency SF
%       value within each row
[cycle/degree]
%SF_v is an array, which store the average spatial frequencies SF
%        value within %each col
[cycle/degree]
%ave_SF_h is the average horizontal spatial frequency SF of total rows
%
[cycle/degree]
%ave_SF_v is the average vertical spatial frequency SF of total columns
%
[cycle/degree]
%ave_radial_SF is the average radial spatial frequency SF
        [cycle/degree]

threshol=1000;              %a threshole value used in the PSD graph;
h_resol=640;          %original horizontal resolution;
v_resol=480;          %original vertical resolution;
h_FOV=48;             %original horizontal FOV;
v_FOV=36;             %original vertical FOV;
h_sr=h_resol/h_FOV;         %original horizontal sampling rate;
v_sr=v_resol/v_FOV;     %original vertical sampling rate;

%Eliminate the edge effect, cut 1% pixels in left, right, top and bottom each
%it is because, during snapshoting of the virual scene, it may introduce some
```

```
%black line in the edge of the picture, it may affect the result of spatial
%frequency of the pitcure

percent=1-(1/100)*2;
new_h_resol=round(h_resol*percent);          %new horizontal resolution;
new_v_resol=round(v_resol*percent);          %new vertical resolution;
new_h_FOV=round(h_FOV*percent);              %new horizontal FOV;
new_v_FOV=round(v_FOV*percent);              %new vertical FOV;
new_h_sr=new_h_resol/new_h_FOV;              %new horizontal sampling rate;
new_v_sr=new_v_resol/new_v_FOV;              %new vertical sampling rate;

%since we have ignored the four edges, when we calculate the average spatial
%freqencies
%the counting is not read from the first row to final row & first column to final
column
%the values should be
new_1st_row=round((v_resol-new_v_resol)/2+1);
new_1st_col=round((h_resol-new_h_resol)/2+1);
new_final_row=new_v_resol+new_1st_row -1;
new_final_col=new_h_resol+new_1st_col-1;


%disp('Initializing the value of SF_h & SF_v at the beginning')
SF_h=0;
SF_v=0;

%disp('-----------------------------------------------------------------');
%disp('');
disp('')
disp('CALCULATE THE AVERAGE HORIZONTAL SPATIAL FREQUENCY OF
THE GRAPH, Please  Wait...')

        for k = new_1st_row : new_final_row,
                        %read the total no. of width files
                %disp('--------------------------------------------------');
                wk = ['w' int2str(k)];
                %int2str convert the integer no. to a string respresentation;
              %read the w1 dile 1st, h2 the 2nd...
                psd_wk=['psd_w' int2str(k)];
                %open a PSD output file to store data for each input files;
                        filename = [wk];                %name of the input
          file;
                        ofilename = [psd_wk '.txt'];    %name of the
          output file;
                    %if ~exist(filename), break, end
                eval(['load ' filename]);
```

```
          %eval function allow to read or stores files in order;
                    x = eval(wk);                    %Process
    data in matrix X;

                      for counter=1:new_h_resol,

    new_x(counter)=x(new_1st_col+counter-1);
                      end

    %since we have eliminated the edges, the original horizontal
    %input
    %should also eliminate the head and tail

    y = psd(new_x);
    eval(['save ' ofilename ' y  -ascii -tabs']);
    m=size(y,1);  %read the cutoff no. of y,
                      %which is about half of the sampling
rate;


    %disp('initializing sort before each run');
    sort=0;
    %array to store the positions where peaks ocurr
              %disp('initializing peak before each run');
              peak=0;                 %the value of the peaks
              %disp('initialize j before each run');
j=0;
    if y(1)>y(2)
          j=j+1; peak(j)=y(1); sort(j)=1;
    else
          j=j;
    end

    for i=2:(m-1),
    if  (y(i)>y(i-1)) & (y(i)>y(i+1))
            j=j+1;  peak(j)=y(i); sort(j)=i;
          else
            j=j;
          end
    end

    if y(m)>y(m-1)
          j=j+1;  peak(j)=y(m); sort(j)=m;
    else
          j=j;
    end
```

```
                        max_no = max(peak);
                        %read the value of the highest peak of PSD graph
                                %disp('initializing sum before each run');
                        sum = 0;
                        %disp('initializing number before each run');
                        number = 0;

                        if peak==0
                            SF_h(k)=0;
                            %disp('********** No peak exist **********');
                        else
                        %disp('********** At least one peak or more exist **********');
                            for counter=1:j,

                                if (peak(counter)>(max_no/2)) &
                                (peak(counter)>threshol)
                                  sum = sum + ((sort(counter)-
                                  1)*((new_h_sr/2)/(m-1))); number=
                                  number+1;
                                 %The no. of sample in a PSD=(FFT
length/2)+1
                                  %Berdat, J.S. and  A.G. Piersol (1980)
                                  Enng.  %Application of correlation and
                                 %and spectral analysis(Wiley:NY)
                                 %number;
                                else
                                 sum = sum; number=number;
                                end
                            end
                            if number == 0
                                SF_h(k)=0;
                            else
                                SF_h(k) = (sum/number);
                            end
                end

                        %disp('Total no. of peaks those values are greater than
                        %0.5*maximum peak value');
                        number;
            end


    total=0;%calculate the average horizontal spatial frequency of the graph
        for file = new_1st_row:new_final_row,
                        total = total + SF_h(file);
```

```
        end

          ave_SF_h=total/new_v_resol;
          ave_SF_h


%disp('############################################################
######');
%disp('############################################################
######');
%disp('############################################################
######');
%disp('');
%disp('');

disp('CALCULATE THE AVERAGE VERTICAL SPATIAL FEQUENCY OF THE
GRAPH, Please   Wait...')
disp('')


                 for k=new_1st_col:new_final_col,
                       %read the total no. of height file;
                                   %read h1 dile 1st, h2 the 2nd...;
                              hk = ['h' int2str(k)];
                             psd_hk=['psd_h' int2str(k)];
                       %open a out file to store PSD data for each input file;
                   filename = [hk];            %name of the input file;
                  ofilename = [psd_hk '.txt'];   %name of the output file;
               %if ~exist(filename), break, end
                   eval(['load ' filename]);
                       %eval function allow to read or store files in order;
                  z = eval(hk);                  % Process data in matrix X.

                   for counter=1:new_v_resol,
                      new_z(counter)=z(new_1st_row + counter -1);
                   end

                   %Since we have eliminate the edges, we should also
eliminate
                   %the head and tail of the input vertical files


                  y = psd(new_z);
                   %calculate the PSD function of the input variable;
                              eval(['save ' ofilename ' y  -ascii -tabs']);
                              m=size(y,1);
```

```
                         %read the cutoff no. of y,
                         %which is about equal half of the sampling
                         rate;


            %disp('initializing sort before each run');
            sort=0;          %array to store the position where peaks
occur;
            %disp('initializing peak before each run');
            peak=0;                 %The value of the peaks;
            %disp('initialize j before each run');
      j=0;
            if y(1)>y(2)
                  j=j+1; peak(j)=y(1); sort(j)=1;
            else
                  j=j;
            end

            for i=2:(m-1),
            if  (y(i)>y(i-1)) & (y(i)>y(i+1))
                     j=j+1;  peak(j)=y(i); sort(j)=i;
                  else
                     j=j;
                  end
            end

            if y(m)>y(m-1)
                  j=j+1;  peak(j)=y(m); sort(j)=m;
            else
                  j=j;
            end

            max_no = max(peak);
            %read the value of the highest peak of PSD graph
                         %disp('initializing sum before each run');
            sum = 0;
            %disp('initializing number before each run');
            number = 0;

            if peak==0
                  SF_v(k)=0;
                  %disp('********** No peak exist **********');
            else

            %disp('********** At least one peak or more exist **********');
                                for counter=1:j,
```

```
                              if (peak(counter)>(max_no/2)) &
                              (peak(counter)>threshol)
                                sum = sum + ((sort(counter)-
                                1)*((new_v_sr/2)/(m-1))); number=
                                number+1;
                               %The no. of sample in a PSD=(FFT
length/2)+1

                                %Berdat, J.S. and  A.G. Piersol (1980)
                                Enng. %Application of correlation and
                               %and spectral analysis(Wiley:NY)

                               number;
                              else
                               sum = sum; number=number;
                              end
                          end
                          if number==0
                              SF_v(k)=0;
                          else
                              SF_v(k) = (sum/number);
                          end

          end

                 %disp('Total no. of peaks those values are greater than
                 0.5*maximum peak value');
                 number;

       end




 total=0;    %calculate the average vertical spatial frequency of the graph
    for file = new_1st_col:new_final_col,
                 total = total + SF_v(file);
     end

       ave_SF_v=total/new_h_resol;
       ave_SF_v

 disp('The average radial spatial frequency of the graph is');
 ave_radial_SF=sqrt((ave_SF_v.^2)+(ave_SF_h.^2))
```

```
SF_h=SF_h';
SF_v=SF_v';
%open a file and write all necessary data
fid=fopen('SP','w');
fprintf(fid, 'Horizontal spatial frequency of each row\n');
fprintf(fid, '%f\n', SF_h);
fprintf(fid, 'Vertical spatial frequency of each column\n');
fprintf(fid, '%f\n', SF_v);
fprintf(fid, 'Average horizontal spatial frequency = %f\n',ave_SF_h);
fprintf(fid, 'Average vertical spatial frequency = %f\n',ave_SF_v);
fprintf(fid, 'Average spatial frequency = %f\n',ave_radial_SF);
fclose('all');
```

Appendix K

This appendix illustartes a motion sickness susceptibility survey. This survey is being conducted to examine the motion sickness susceptibility of the subjects. Details of experiments are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

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的調查，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.

暈浪的定義就是一種病徵，例如流汗，作嘔，頭暈，頭痛或嘔吐。

1. In the past 12 months how often have you experienced motion sickness while traveling 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)

   在過去十二個月中有否在乘搭交通公具中有暈浪的經驗？(例如：當你在三百次乘搭巴士經驗中，有三十次感到暈浪不適，答案就是10%)

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 輪 渡	0%	1%-10%	11%-40%	41%-74%	75%-100%
Jet-Foil 飛翔船	0%	1%-10%	11%-40%	41%-74%	75%-100%
Trains (KCR/MTR) 火 車	0%	1%-10%	11%-40%	41%-74%	75%-100%
Elevators 升降機	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
Bus 巴 士	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Cross-Ferry 輪 渡	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 (KCR/MTR) 火 車	Sweating 流汗	Nausea 作嘔	Dizziness 頭暈	Headache 頭痛	Vomiting 嘔吐
Elevators 升降機	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幾大？

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

Comments:

其它意見： ____________________

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

多謝你的參與，如有問題可找：

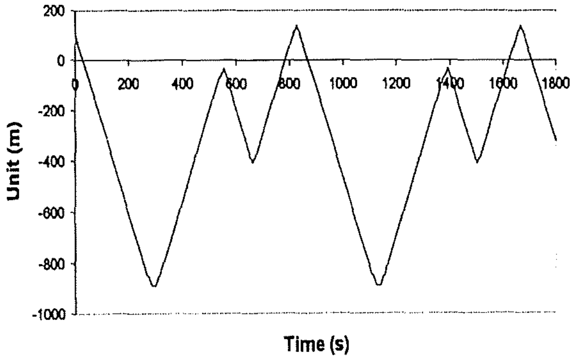
Colleen Finney or 或 Dr. R.H.Y So

e-mail: mica@uxmail.ust.hk e-mail: rhyso@uxmail.ust.hk

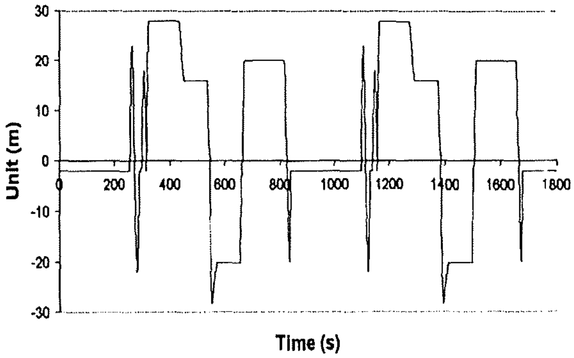
Appendix L

This appendix illustrates the scene displacement graphs in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes of scene velocity level 1 of Experiment two. Details of the experiment are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

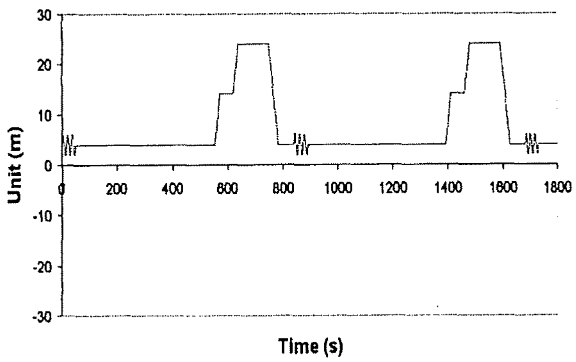
Translational displacement in x-axis



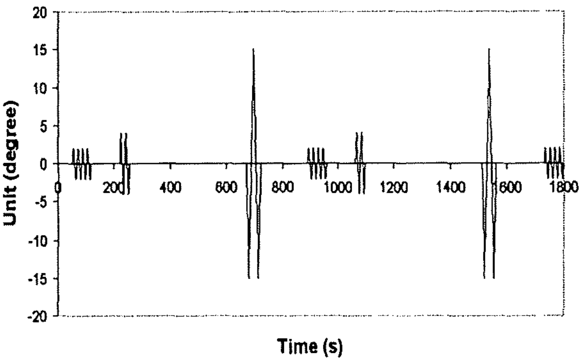
Translational displacement in y-axis



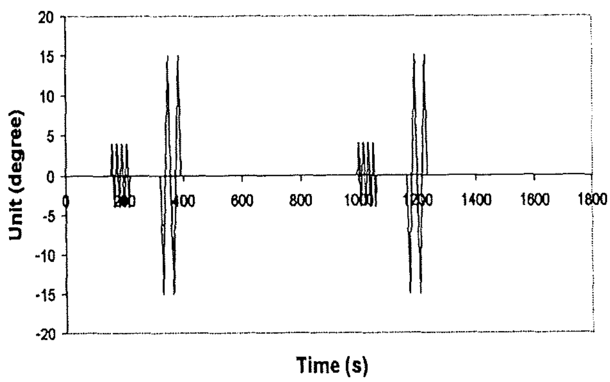
Translational displacement in z-axis



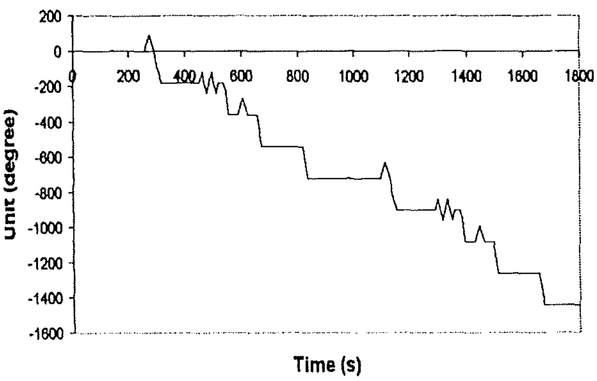
Angular motion in roll axis



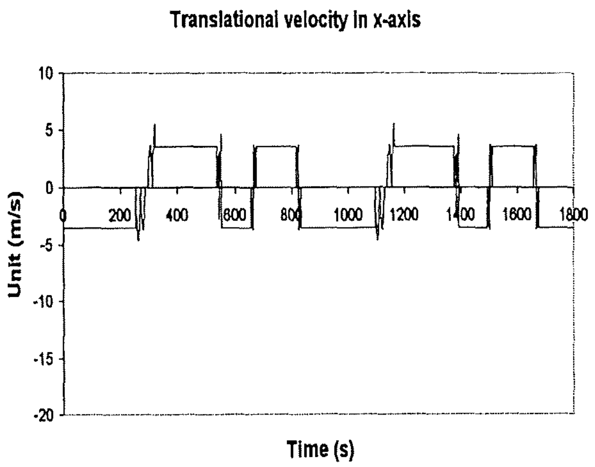
Angular motion in pitch axis

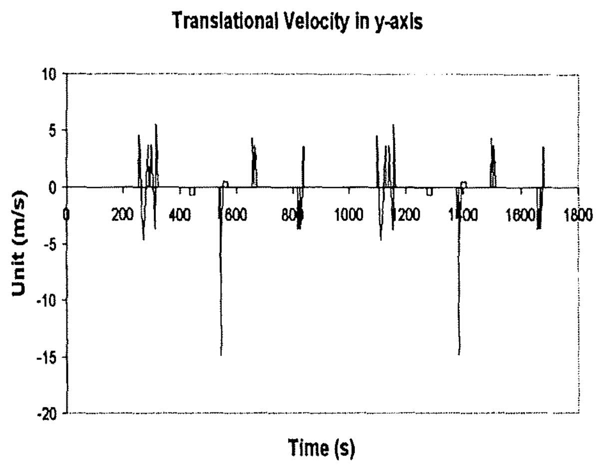


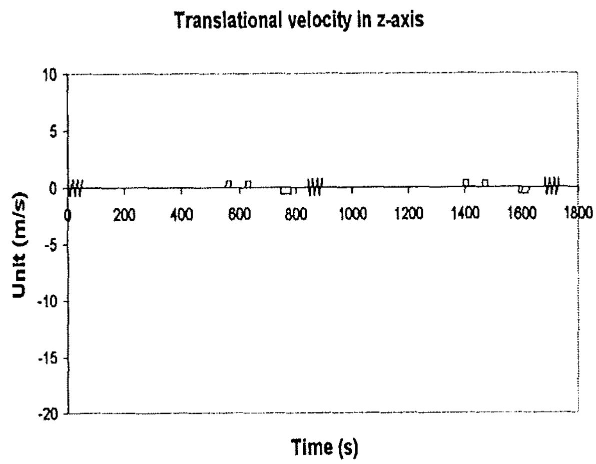
Angular motion in yaw axis

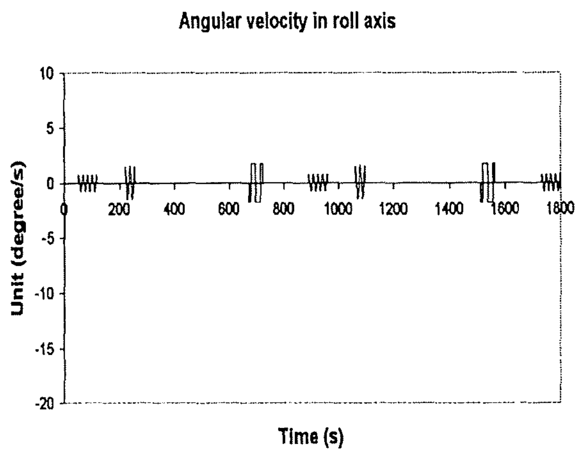


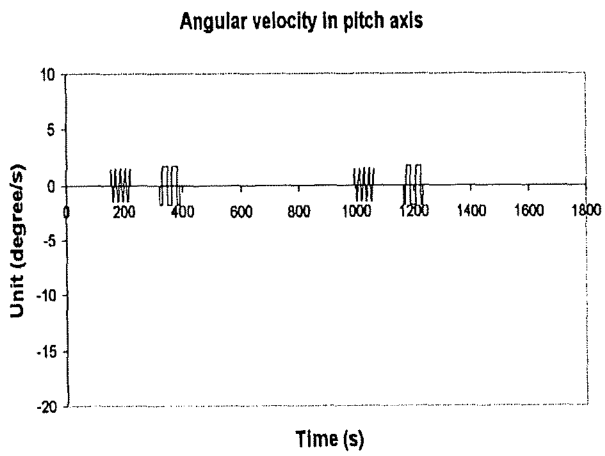
This appendix illustrates the scene velocity graphs in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes of scene velocity level 1 of Experiment two. Details of the experiment are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

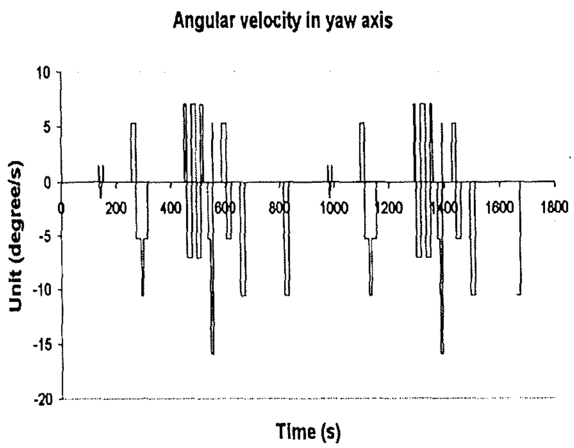






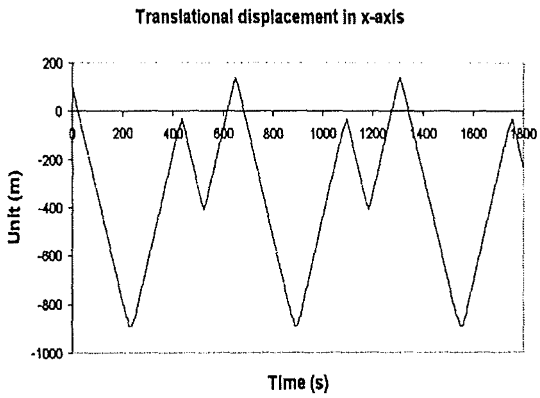


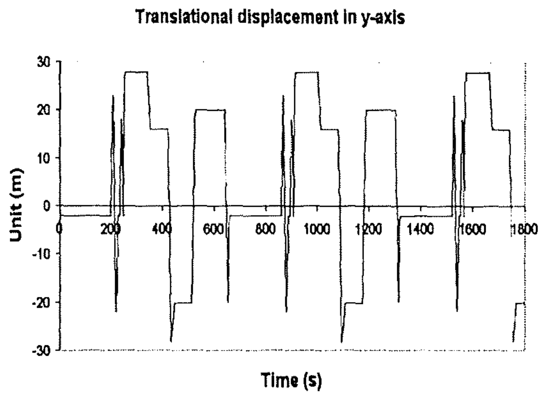


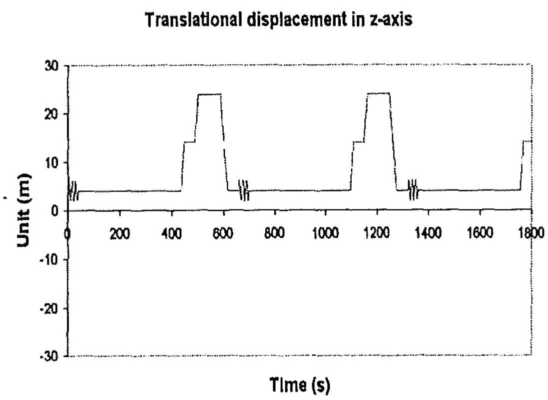


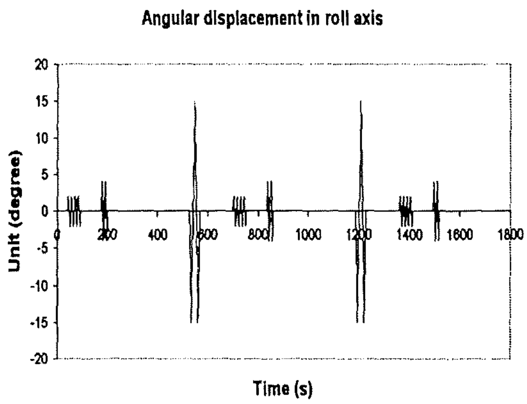
Appendix M

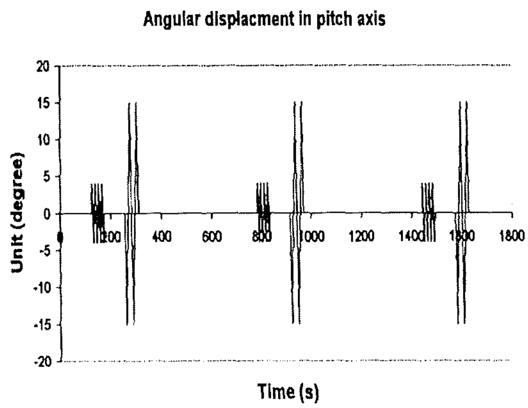
This appendix illustrates the scene displacement graphs in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes of scene velocity level 2 of Experiment two. Details of the experiment are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

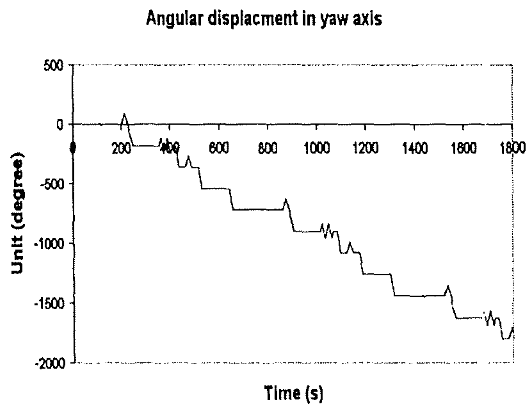




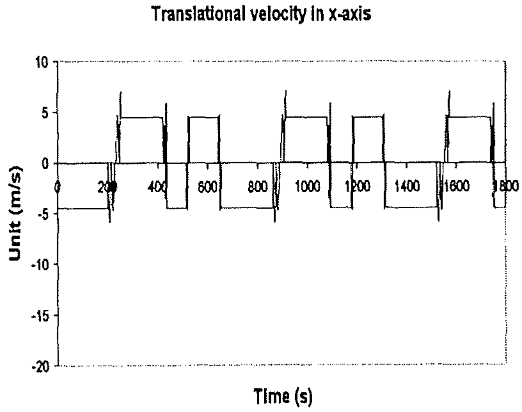


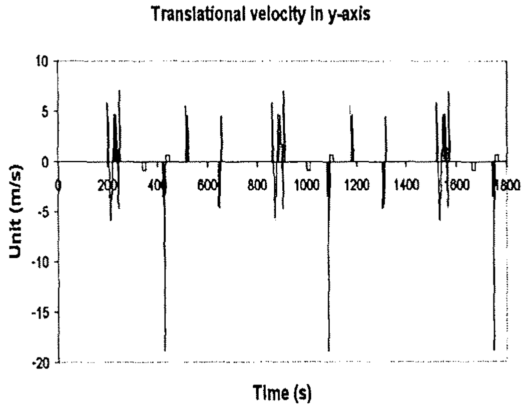


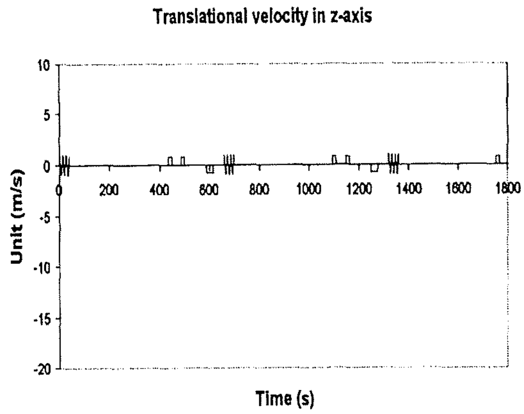


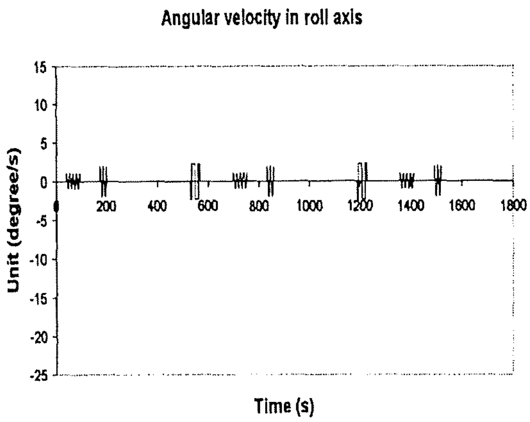


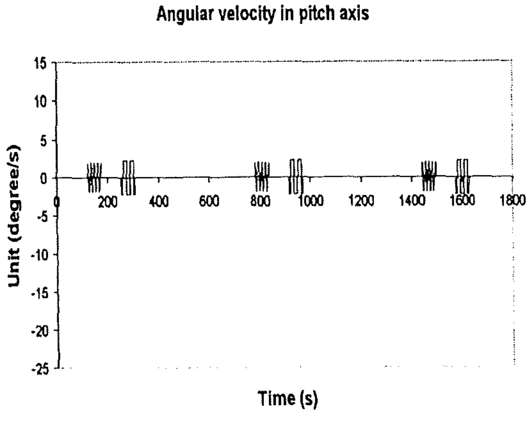
This appendix illustrates the scene velocity graphs in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes of scene velocity level 2 of Experiment two. Details of the experiment are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

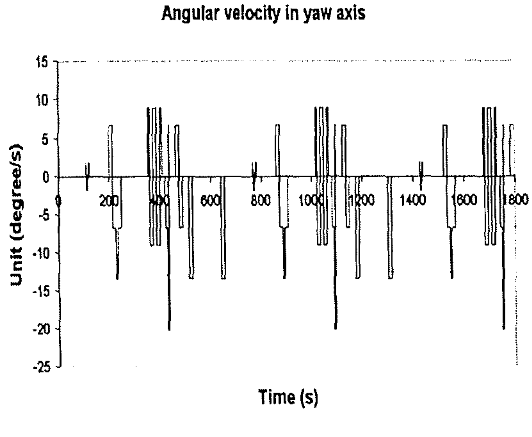








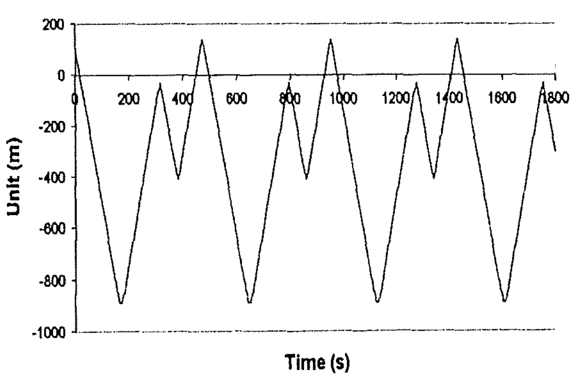




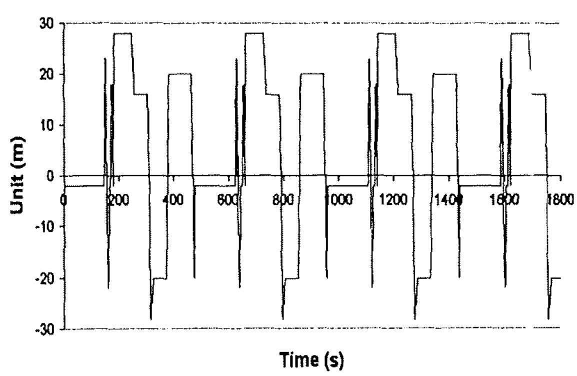
Appendix N

This appendix illustrates the scene displacement graphs in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes of scene velocity level 3 of Experiment two. Details of the experiment are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

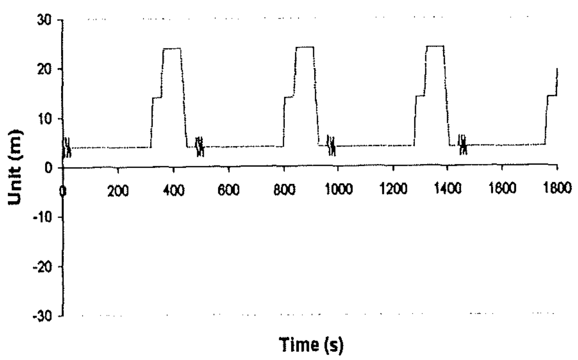
Translational displacement in z-axis



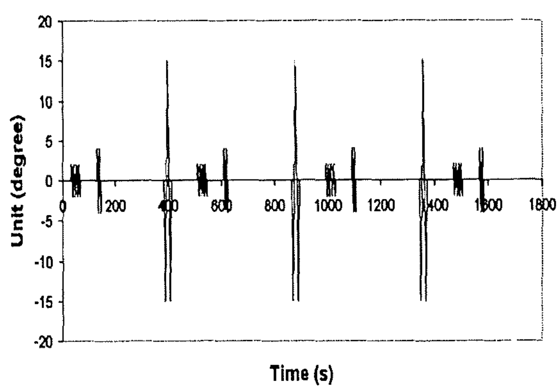
Translational displacement in y-axis



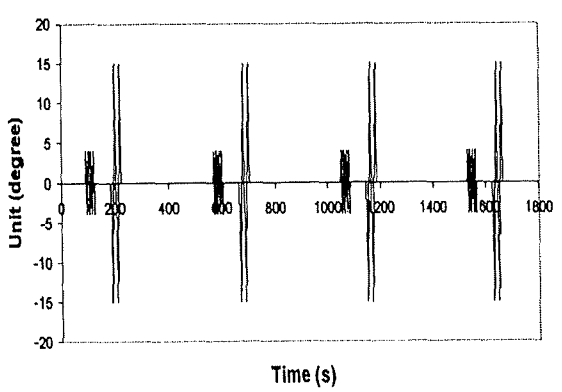
Translational displacement in z-axis



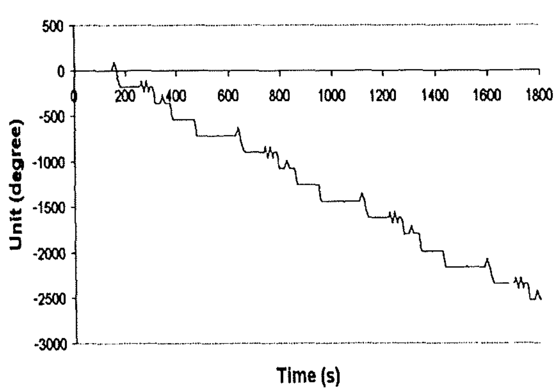
Angular displacement in roll axis



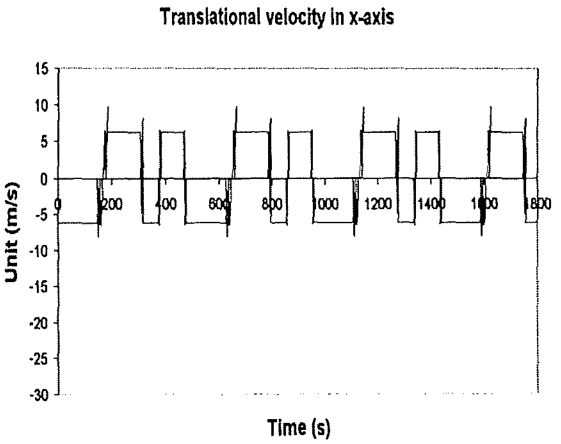
Angular displacement in pitch axis

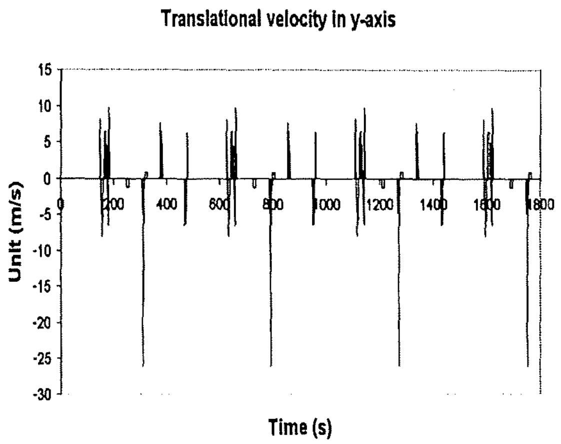


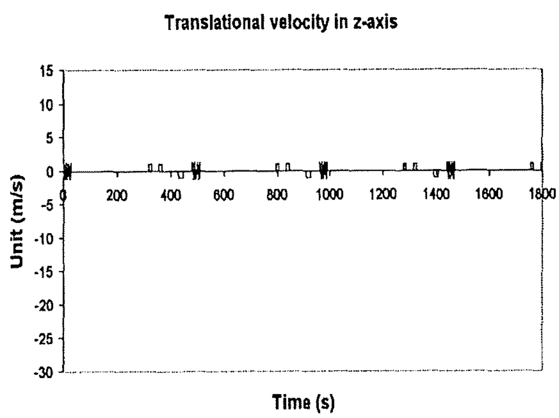
Angular displacement in yaw axis

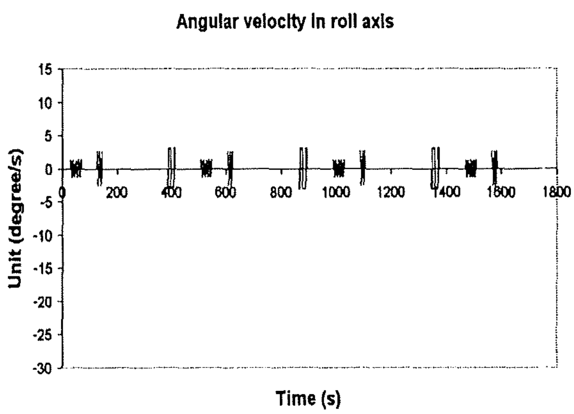


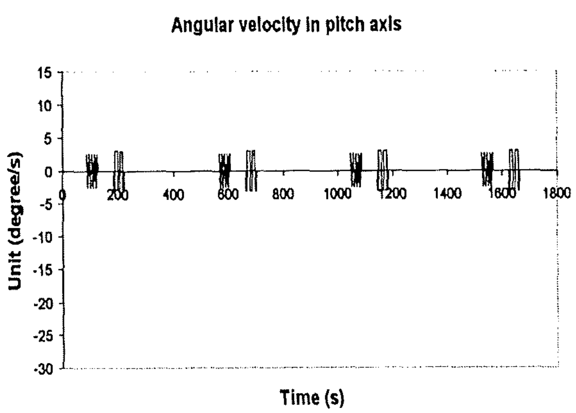
This appendix illustrates the scene velocity graphs in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes of scene velocity level 3 of Experiment two. Details of the experiment are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

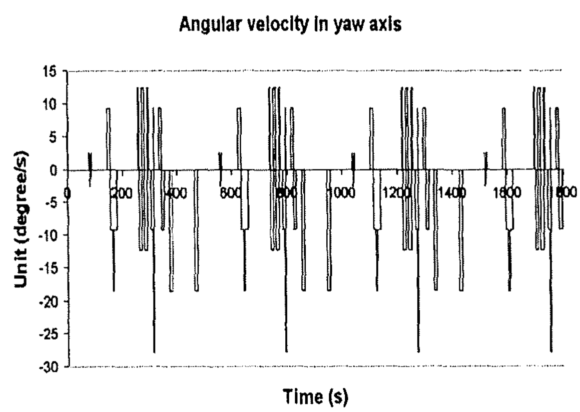








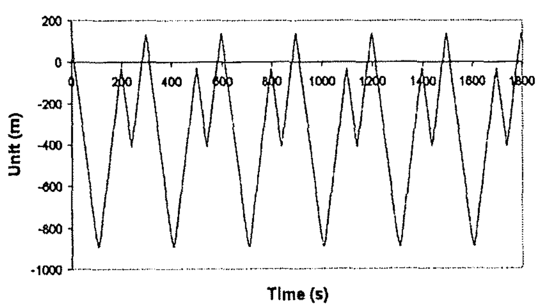




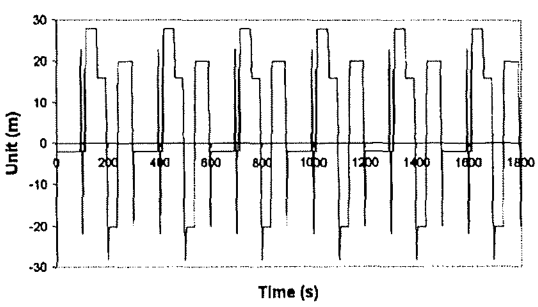
Appendix O

This appendix illustrates the scene displacement graphs in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes of scene velocity level 4 of Experiment two. Details of the experiment are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

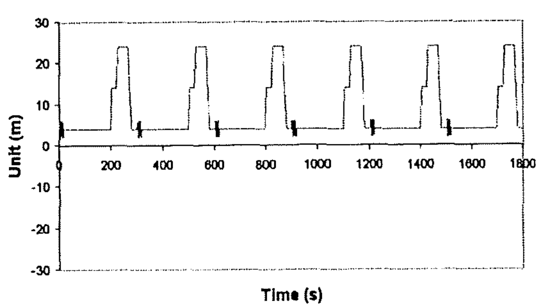
Translational displacement in x-axis



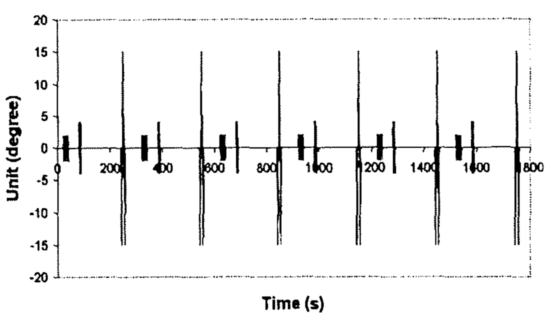
Translational displacement in y-axis



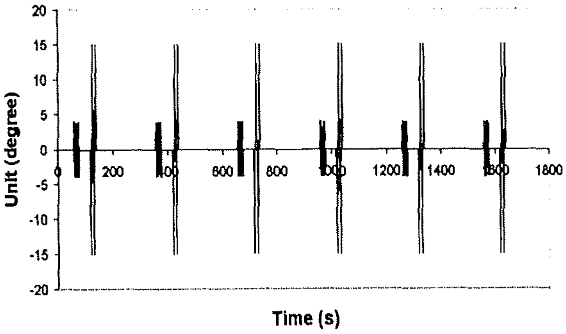
Translational displacement in z-axis



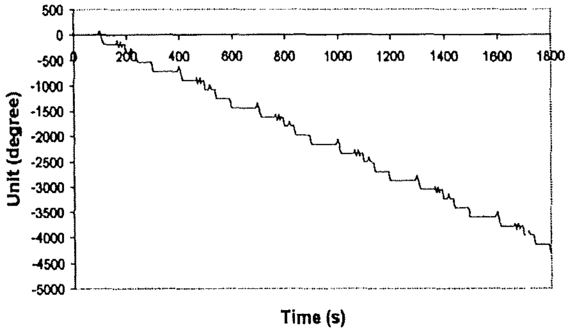
Angular displacment in roll axis



Angular displacment in pitch axis

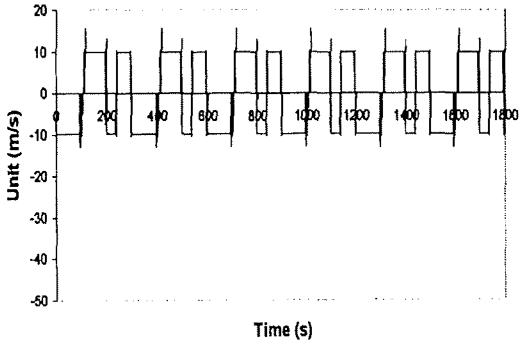


Angular displacement in yaw axis

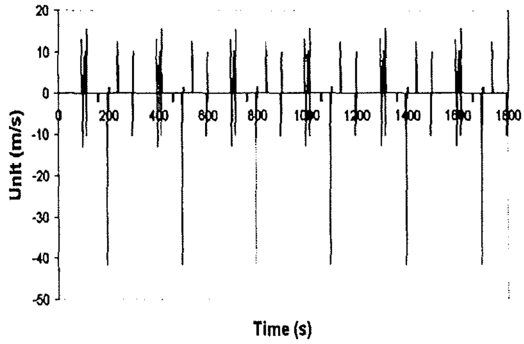


This appendix illustrates the scene velocity graphs in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes of scene velocity level 4 of Experiment two. Details of the experiment are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

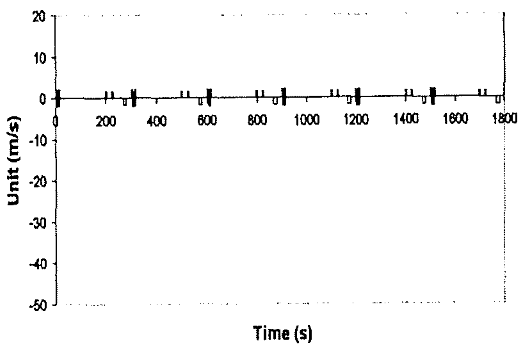
Translational velocity in x-axis



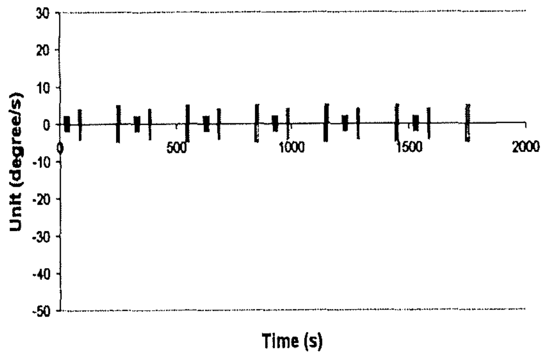
Translation Velocity in y-axis



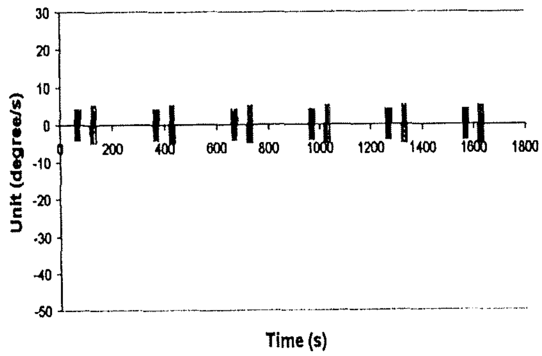
Translational velocity in z-axis



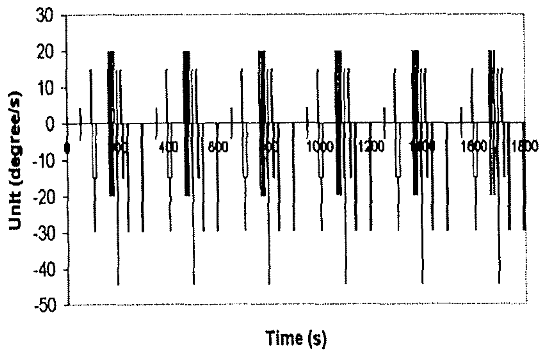
Angular velocity in roll axis



Angular velocity in pitch axis

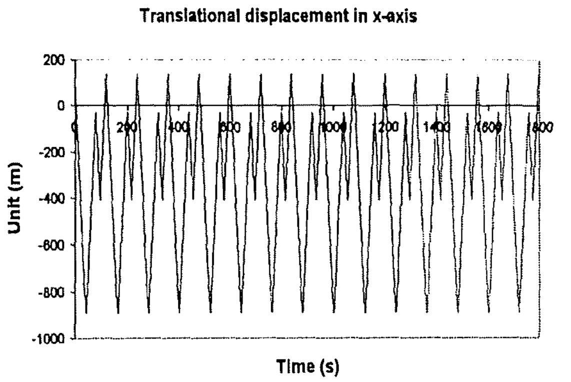


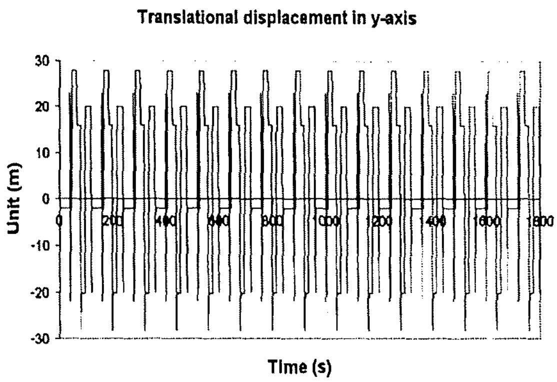
Angular velocity in yaw axis

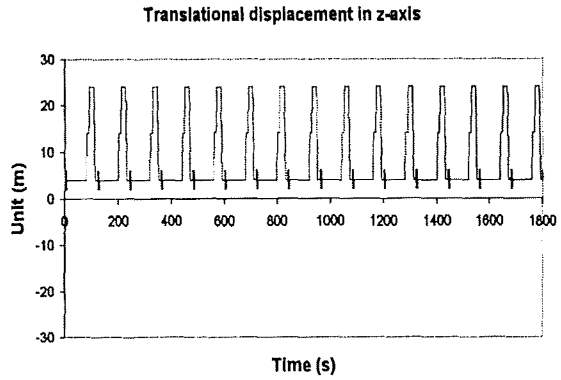


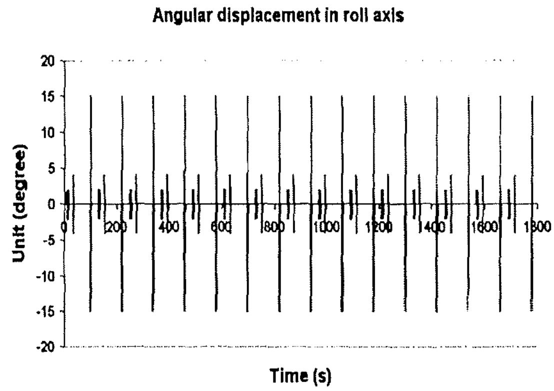
Appendix P

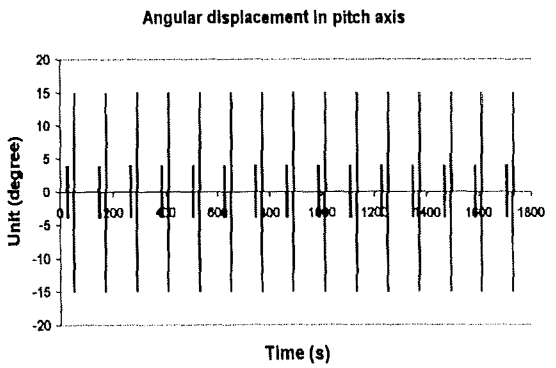
This appendix illustrates the scene displacement graphs in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes of scene velocity level 5 of Experiment two. Details of the experiment are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

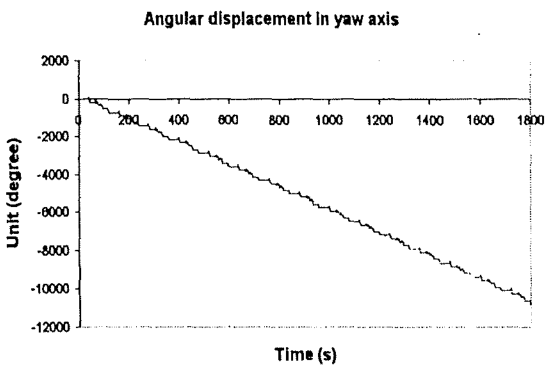




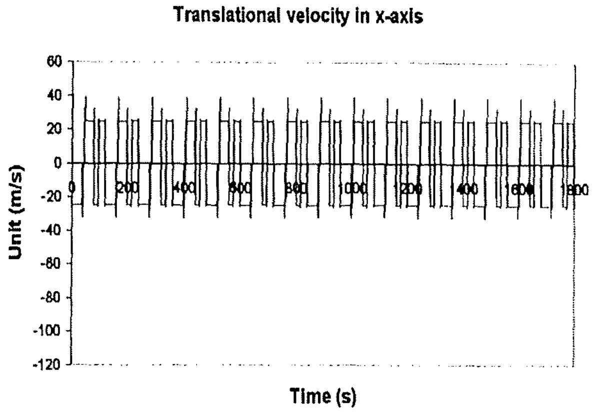


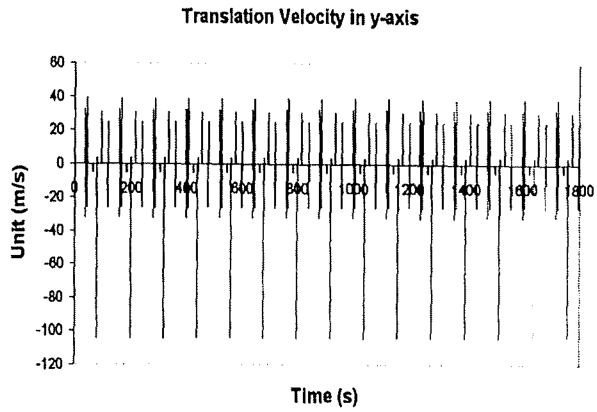


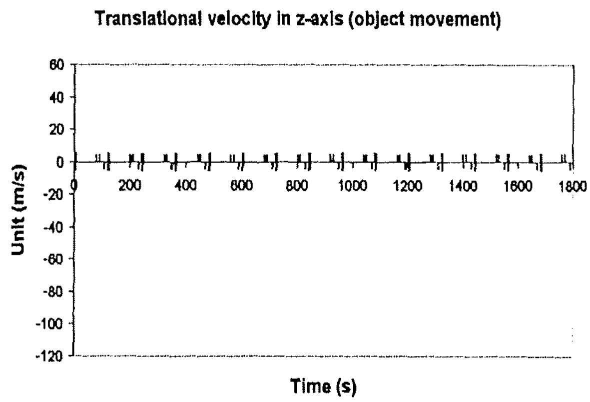


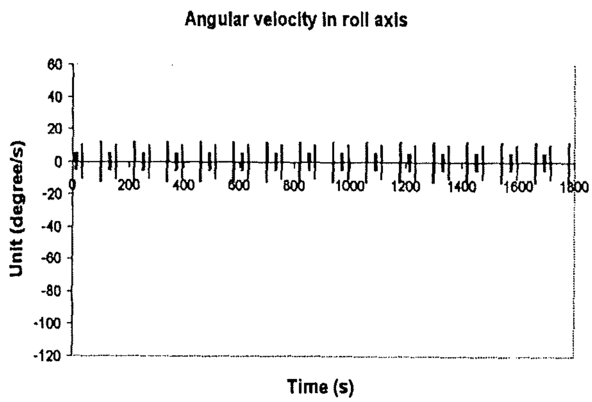


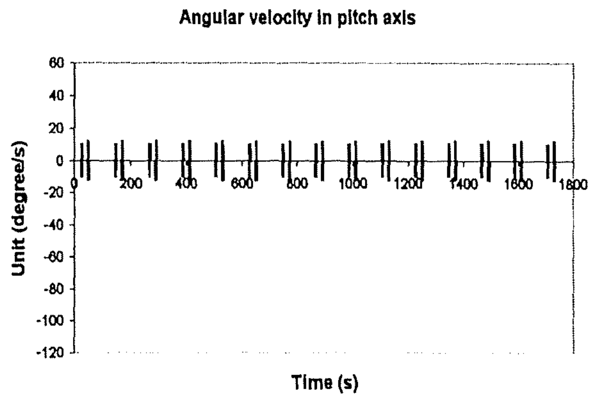
This appendix illustrates the scene velocity graphs in x (fore-and-aft), y (lateral), z (vertical), pitch, yaw and roll axes of scene velocity level 5 of Experiment two. Details of the experiment are documented in Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system).

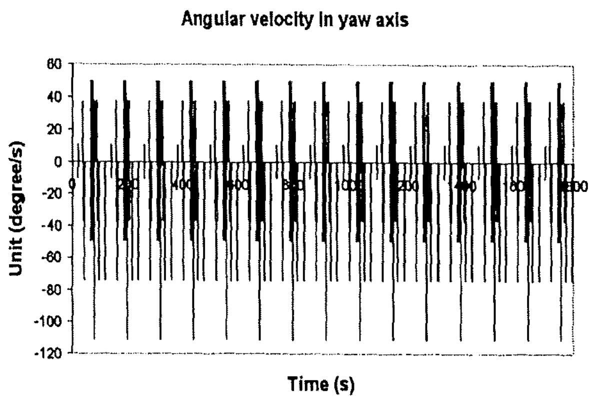












Appendix Q

This appendix illustrates the statistical results of Experiment two. Chapter 8 (Studies of effects of scene velocity on cybersickness with a head-coupled virtual reality system) is related to this appendix.

Experimental studies of effects of scene velocity on cybersickess with a head-coupled virtual reality system

Table Q.1 ANOVA result for nausea ratings in 5 different scene velocity conditions

Source	DF	SS	Mean Square	F Value	Pr > F
Scene velocity	4	113.652381	28.413095	14.87	0.0001*
Duration	6	333.866667	55.644444	29.12	0.0001*
Scene velocity * duration	24	36.180952	1.507540	0.79	0.7515
Error	385	735.583333	1.910606		

(Note that * indicate a significant effect at p=0.05)

Table Q.2 SNK test on the effect of scene velocity on nausea

SNK Grouping	Mean	N	Scene velocity
A	2.0476	84	level 4
A			
A	1.7262	84	level 5
B	1.0833	84	level 2
B			
B	0.8929	84	level 3
B			
B	0.6667	84	level 1

(Note that means with the same letter are not significantly different)

Table Q.3 SNK test on the effect of duration on nausea ratings

SNK Grouping		Mean	N	Duration (minutes)
	A	2.5667	60	30
	A			
	A	2.2500	60	25
	B	1.6833	60	20
	B			
C	B	1.3333	60	15
C				
C		0.8667	60	10
	D	0.2833	60	5
	D			
	D	0.0000	60	0

(Note that means with the same letter are not significantly different)

Table Q.4a ANOVA result on the effect of duration on nausea ratings of each condition individually (5 conditions)

Scene velocity level 1					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (duration)	6	31.1666667	5.1944444	9.19	0.0001*
Error	77	43.5000000	0.5649351		
Scene velocity level 2					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (duration)	6	46.0000000	7.6666667	9.16	0.0001*
Error	77	64.4166667	0.8365801		
Scene velocity level 3					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (duration)	6	47.9523810	7.9920635	7.15	0.0001*
Error	77	86.0833333	1.1179654		
Scene velocity level 4					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (duration)	6	126.142857	21.023810	4.66	0.0004*
Error	77	347.666667	4.515152		
Scene velocity level 5					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (duration)	6	118.785714	19.797619	7.86	0.0001*
Error	77	193.916667	2.518398		

(Note that * indicate a significant effect at p=0.05)

Table Q.4b. SNK test on the effect of duration on nausea ratings of each condition individually (Scene velocity level 1, 2,3)

Scene velocity level 1					
SNK Grouping			Mean	N	Duration (minutes)
	A		1.7500	12	30
	A				
B	A		1.2500	12	25
B					
B	C		0.9167	12	20
	C				
D	C		0.4167	12	15
D	C				
D	C		0.2500	12	10
D					
D			0.0833	12	5
D			0.0000	12	0
Scene velocity level 2					
SNK Grouping			Mean	N	Duration (minutes)
	A		2.1667	12	30
	A				
	A		1.9167	12	25
	A				
B	A		1.4167	12	20
B					
B	C		1.0000	12	15
B	C				
B	C	D	0.7500	12	10
	C	D			
	C	D	0.3333	12	5
		D			
		D	0.0000	12	0
Scene velocity level 3					
SNK Grouping			Mean	N	Duration (minutes)
	A		2.0833	12	30
	A				
B	A		1.7500	12	25
B	A				
B	A	C	1.1667	12	20
B		C			
B		C	0.8333	12	15
		C			
		C	0.3333	12	10
		C			
		C	0.0833	12	5
		C	0.0000	12	0

(Note that means with the same letter are not significantly different)

Table Q.4b. SNK test on the effect of duration on nausea ratings of each condition individually (Scene velocity levels 4 & 5)

Scene velocity level 4					
SNK Grouping			Mean	N	Duration (minutes)
	A		3.5833	12	30
	A				
	A		3.2500	12	25
	A				
B	A		2.6667	12	20
B	A				
B	A		2.4167	12	15
B	A				
B	A	C	1.7500	12	10
B		C			
B		C	0.6667	12	5
		C			
		C	0.0000	12	0

Scene velocity level 5					
SNK Grouping			Mean	N	Duration (minutes)
	A		3.2500	12	30
	A				
	A		3.0833	12	25
	A				
B	A		2.2500	12	20
B	A				
B	A		2.0000	12	15
B					
B	C		1.2500	12	10
	C				
	C		0.2500	12	5
	C				
	C		0.0000	12	0

(Note that means with the same letter are not significantly different)

Table Q.5 ANOVA result for apparent self-motion ratings in 5 different scene velocity conditions

Source	DF	SS	Mean Square	F Value	Pr > F
Scene velocity	4	12.176190	3.044048	5.13	0.0005*
Duration	6	120.414286	20.069048	33.79	0.0001*
Scene velocity * Duration	24	6.657143	0.277381	0.47	0.9862
Error	385	228.666667	0.593939		

(Note that * indicate a significant effect at p=0.05)

Table Q.6 SNK test on the effect of scene velocity on apparent self-motion ratings

SNK Grouping		Mean	N	Scene velocity
	A	1.2976	84	level 4
	A			
B	A	1.0952	84	level 5
B				
B		0.9762	84	level 2
B				
B		0.8929	84	level 3
B				
B		0.8095	84	level 1

(Note that means with the same letter are not significantly different)

Table Q.7 SNK test on the effect of duration on apparent self-motion ratings

SNK Grouping		Mean	N	duration (minutes)
	A	1.6333	60	30
	A			
B	A	1.5000	60	25
B	A			
B	A	1.3333	60	20
B				
B		1.1833	60	15
	C	0.9000	60	10
	D	0.5500	60	5
	E	0.0000	60	0

(Note that means with the same letter are not significantly different)

Table Q.8a. ANOVA result on the effect of duration on apparent self-motion ratings of each condition individually (5 conditions)

Source	DF	SS	Mean Square	F Value	Pr > F
Scene velocity level 1					
Model (duration)	6	16.9523810	2.8253968	6.04	0.0001*
Error	77	36.0000000	0.4675325		
Scene velocity level 2					
Model (duration)	6	18.7857143	3.1309524	6.86	0.0001*
Error	77	35.1666667	0.4567100		
Scene velocity level 3					
Model (duration)	6	17.9523810	2.9920635	5.75	0.0001*
Error	77	40.0833333	0.5205628		
Scene velocity level 4					
Model (duration)	6	36.4761905	6.0793651	7.19	0.0001*
Error	77	65.0833333	0.8452381		
Scene velocity level 5					
Model (duration)	6	36.9047619	6.1507937	9.05	0.0001*
Error	77	52.3333333	0.6796537		

(Note that * indicate a significant effect at p=0.05)

Table Q.8b SNK test on the effect of duration on apparent self-motion ratings of each condition individually (scene velocity level 1, 2 &3)

Scene velocity level 1					
SNK Grouping			Mean	N	Duration (minutes)
	A		1.4167	12	30
	A				
B	A		1.1667	12	25
B	A				
B	A		1.0833	12	20
B	A				
B	A		0.9167	12	15
B	A				
B	A	C	0.6667	12	10
B		C			
B		C	0.4167	12	5
		C			
		C	0.0000	12	0
Scene velocity level 2					
SNK Grouping			Mean	N	Duration (minutes)
	A		1.3333	12	20
	A				
	A		1.3333	12	25
	A				
	A		1.3333	12	30
	A				
	A		1.2500	12	15
	A				
	A		1.0000	12	10
	A				
	A		0.5833	12	5
	B		0.0000	12	0
Scene velocity level 3					
SNK Grouping			Mean	N	Duration (minutes)
	A		1.5000	12	30
	A				
B	A		1.2500	12	25
B	A				
B	A		1.1667	12	20
B	A				
B	A		1.0000	12	15
B	A				
B	A		0.7500	12	10
B					
B	C		0.5833	12	5
	C		0.0000	12	0

(Note that means with the same letter are not significantly different)

Table Q.8b SNK test on the effect of duration on apparent self-motion ratings of each condition individually (scene velocity level 4 &5)

SNK Grouping		Mean	N	Duration (minute)
Scene velocity level 4				
	A	2.0000	12	30
	A			
	A	1.9167	12	25
	A			
B	A	1.6667	12	20
B	A			
B	A	1.5000	12	15
B	A			
B	A	1.2500	12	10
B				
B		0.7500	12	5
	C	0.0000	12	0

SNK Grouping		Mean	N	Duration (minutes)
Scene velocity level 5				
	A	1.9167	12	30
	A			
	A	1.8333	12	25
	A			
B	A	1.4167	12	20
B	A			
B	A	1.2500	12	15
B				
B	C	0.8333	12	10
	C			
D	C	0.4167	12	5
D				
D		0.0000	12	0

(Note that means with the same letter are not significantly different)

Table Q.9 The descriptive statistics of the pre, post and change sickness score (Nausea, Oculomotor)

		Nausea	sub-scale		
Scene Velocity		Time	N	Mean	SD
Level	1	Post	12	19.0800	22.2806
Level	1	Pre	12	0.7950	2.7540
Level	1	Change	12	18.2850	20.9242
Level	2	Post	12	28.6200	27.2881
Level	2	Pre	12	1.5900	3.7134
Level	2	Change	12	27.0300	27.5396
Level	3	Post	12	25.4400	34.3568
Level	3	Pre	12	1.5900	5.5079
Level	3	Change	12	23.8500	34.6367
Level	4	Post	12	51.6750	39.3257
Level	4	Pre	12	0.7950	2.7540
Level	4	Change	12	50.8800	40.1326
Level	5	Post	12	40.5450	31.2790
Level	5	Pre	12	1.5900	3.7134
Level	5	Change	12	38.9550	32.1486
		Oculomotor	sub-scale		
Scene	velocity	Time	N	Mean	SD
Level	1	Post	12	33.4783	25.7473
Level	1	Pre	12	3.7900	6.8564
Level	1	Change	12	29.6883	24.2858
Level	2	Post	12	36.0050	24.2140
Level	2	Pre	12	3.1583	5.0677
Level	2	Change	12	32.8467	24.8964
Level	3	Post	12	27.7933	19.7486
Level	3	Pre	12	5.6850	8.6274
Level	3	Change	12	22.1083	18.4141
Level	4	Post	12	34.1100	24.5088
Level	4	Pre	12	3.7900	6.8564
Level	4	Change	12	30.3200	19.9241
Level	5	Post	12	39.7950	24.2140
Level	5	Pre	12	4.4217	6.0106
Level	5	Change	12	35.3733	22.7017

Table Q.9 The descriptive statistics of the pre, post and change sickness score (Disorientation, Total sickness score)

		Disorientation	sub-scale		
Scene	velocity	Time	N	Mean	SD
Level	1	Post	12	33.6400	29.9483
Level	1	Pre	12	2.3200	5.4184
Level	1	Change	12	31.3200	27.9190
Level	2	Post	12	27.8400	27.1999
Level	2	Pre	12	1.1600	4.0184
Level	2	Change	12	26.6800	27.4951
Level	3	Post	12	24.3600	30.9131
Level	3	Pre	12	0.0000	0.0000
Level	3	Change	12	24.3600	30.9131
Level	4	Post	12	42.9200	32.7575
Level	4	Pre	12	2.3200	5.4184
Level	4	Change	12	40.6000	31.1025
Level	5	Post	12	48.7200	37.7733
Level	5	Pre	12	1.1600	4.0184
Level	5	Change	12	47.5600	35.8390

	Total	sickness	score		
Scene	velocity	Time	N	Mean	SD
Level	1	Post	12	33.0367	26.8198
Level	1	Pre	12	2.8050	5.0744
Level	1	Change	12	30.2317	25.4389
Level	2	Post	12	36.4650	28.3543
Level	2	Pre	12	2.4933	4.6036
Level	2	Change	12	33.9717	28.7699
Level	3	Post	12	30.2317	28.9900
Level	3	Pre	12	3.4283	6.2701
Level	3	Change	12	26.8033	29.2248
Level	4	Post	12	48.6200	34.6833
Level	4	Pre	12	2.8050	5.0744
Level	4	Change	12	45.8150	32.2566
Level	5	Post	12	48.6200	29.4056
Level	5	Pre	12	3.1167	4.4634
Level	5	Change	12	45.5033	28.4309

Table Q.10. ANOVA result on Nausea sub-score of pre immersion profiles

Source	DF	SS	Mean Square	F Value	Pr > F
Model (scene velocity)	4	9.10116000	2.27529000	0.16	0.9596
Error	55	803.9358000	14.61701455		

Table Q.11. ANOVA result on Oculomotor sub-score of pre immersion profiles

Source	DF	SS	Mean Square	F Value	Pr > F
Model (scene velocity)	4	44.049907	11.0124767	0.24	0.9150
Error	55	2532.86963	46.0521752		

Table Q.12. ANOVA result on Disorientation sub-score of pre immersion profiles

Source	DF	SS	Mean Square	F Value	Pr > F
Model (scene velocity)	4	45.212160	11.3030400	0.62	0.6495
Error	55	1001.12640	18.2022982		

Table Q.13. ANOVA result on Total Sickness score of pre immersion profiles

Source	DF	SS	Mean Square	F Value	Pr > F
Model (scene velocity)	4	6.06129333	1.51532333	0.06	0.9937
Error	55	1451.2135000	26.38570000		

Table Q.14. ANOVA result on Nausea sub-score (comparison between pre and post- immersion profiles)

Scene velocity level 1					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	2006.04735	2006.04735	7.96	0.0099*
Error	22	5544.12330	252.00560		
Scene velocity level 2					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	4383.72540	4383.72540	11.56	0.0026*
Error	22	8342.73000	379.21500		
Scene velocity level 3					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	3412.93500	3412.93500	5.64	0.0267*
Error	22	13318.03080	605.36504		
Scene velocity level 4					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	15532.6464	15532.6464	19.99	0.0002*
Error	22	17095.0122	777.0460		
Scene velocity level 5					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	9104.95215	9104.95215	18.35	0.0003*
Error	22	10913.80770	496.08217		

(Note that * indicate a significant effect at p=0.05)

Table Q.15. ANOVA result on Oculomotor sub-score (comparison between pre and post- immersion profiles)

Source	DF	SS	Mean Square	F Value	Pr > F
Scene velocity level 1					
Model	1	5288.38282	5288.38282	14.90	0.0008*
Error	22	7809.28237	354.96738		
Scene velocity level 2					
Model	1	6473.42107	6473.42107	21.16	0.0001*
Error	22	6731.97487	305.99886		
Scene velocity level 3					
Model	1	2932.67042	2932.67042	12.63	0.0018*
Error	22	5108.83157	232.21962		
Scene velocity level 4					
Model	1	5515.81440	5515.81440	17.03	0.0004*
Error	22	7124.59360	323.84516		
Scene velocity level 5					
Model	1	7507.63627	7507.63627	24.12	0.0001*
Error	22	6846.88767	311.22217		

(Note that * indicate a significant effect at p=0.05)

Table Q.16. ANOVA result on Disorientation sub-score (comparison between pre and post- immersion profiles)

Source	DF	SS	Mean Square	F Value	Pr > F
Scene velocity level 1					
Model	1	5885.65440	5885.65440	12.71	0.0017*
Error	22	10188.88320	463.13105		
Scene velocity level 2					
Model	1	4270.93440	4270.93440	11.30	0.0028*
Error	22	8315.80800	377.99127		
Scene velocity level 3					
Model	1	3560.45760	3560.45760	7.45	0.0122*
Error	22	10511.82720	477.81033		
Scene velocity level 4					
Model	1	9890.16000	9890.16000	17.94	0.0003*
Error	22	12126.54720	551.20669		
Scene velocity level 5					
Model	1	13571.7216	13571.7216	18.81	0.0003*
Error	22	15872.6976	721.4863		

Table Q.17. ANOVA result on Total Sickness score (comparison between pre and post- immersion profiles)

Source	DF	SS	Mean Square	F Value	Pr > F
Scene velocity level 1					
Model	1	5483.72202	5483.72202	14.72	0.0009*
Error	22	8195.56797	372.52582		
Scene velocity level 2					
Model	1	6924.44482	6924.44482	16.78	0.0005*
Error	22	9076.78677	412.58122		
Scene velocity level 3					
Model	1	4310.51207	4310.51207	9.80	0.0049*
Error	22	9677.08793	439.86763		
Scene velocity level 4					
Model	1	12594.0854	12594.0854	20.50	0.0002*
Error	22	13515.5185	614.3417		
Scene velocity level 5					
Model	1	12423.3201	12423.3201	28.09	0.0001*
Error	22	9730.7071	442.3049		

(Note that * indicate a significant effect at p=0.05)

Table Q.18 ANOVA result for Nausea sub-score of the change sickness profiles in 5 different scene velocity conditions

Source	DF	Squares	Square	F Value	Pr > F
Model	4	8206.21260	2051.55315	2.04	0.1021
Error	55	55441.23300	1008.02242		

(Note that * indicate a significant effect at p=0.05)

Table Q.19 ANOVA result for Oculomotor sub-score of the change sickness profiles in 5 different scene velocity conditions

Source	DF	Squares	Square	F Value	Pr > F
Model	4	1193.17791	298.29448	0.61	0.6600
Error	55	27071.54047	492.20983		

(Note that * indicate a significant effect at p=0.05)

Table Q.20 ANOVA result for Disorientation sub-score of the change sickness profiles in 5 different scene velocity conditions

Source	DF	Squares	Square	F Value	Pr > F
Model	4	4572.88704	1143.22176	1.21	0.3191
Error	55	52171.60320	948.57460		

(Note that * indicate a significant effect at p=0.05)

Table Q.21 ANOVA result for Total sickness score of the change sickness profiles in 5 different scene velocity conditions

Source	DF	Squares	Square	F Value	Pr > F
Model	4	3690.39513	922.59878	1.10	0.3639
Error	55	45955.09417	835.54717		

(Note that * indicate a significant effect at p=0.05)

Table Q.22 ANOVA result for Q1 to Q6 of simulation assessment question

Q1: Did you feel you were moving during the experiment?					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (scene velocity)	4	1.76666667	0.44166667	0.57	0.6836
Error	55	42.41666667	0.77121212		
Q2: How uncomforted of HMD?					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (scene velocity)	4	3.56666667	0.89166667	1.22	0.3125
Error	55	40.16666667	0.73030303		
Q3: How completely did you believe you were part of virtual environment?					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (scene velocity)	4	5.06666667	1.26666667	1.81	0.1409
Error	55	38.58333333	0.70151515		
Q4: How flat and missing in depth did the world appear?)					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (scene velocity)	4	4.43333333	1.10833333	2.57	0.0481
Error	55	23.75000000	0.43181818		
Q5: How excited do you feel after the experiment?					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (scene velocity)	4	3.06666667	0.76666667	1.15	0.3418
Error	55	36.58333333	0.66515152		
Q6: How real was the graph simulation?					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (scene velocity)	4	6.43333333	1.60833333	3.10	0.0225
Error	55	28.50000000	0.51818182		

(Note that * indicate a significant effect at p=0.05)

Appendix R

This appendix illustrates the statistical results of Experiment three. Chapter 9 (Studies of effects of scene complexity on cybersickness with a head-coupled virtual reality system) is related to this appendix.

Experimental studies of effects of scene complexity on cybersickess with a head-coupled virtual reality system

Table R.1 ANOVA result for nausea ratings in 3 different scene complexity conditions

Source	DF	SS	Mean Square	F Value	Pr > F
Scene complexity	2	142.055556	71.027778	34.48	0.0001*
Duration	6	123.539683	20.589947	10.00	0.0001*
Scene complexity * Duration	12	45.555556	3.796296	1.84	0.0426*
Error	231	475.833333	2.059885		

(Note that * indicate a significant effect at p=0.05)

Table R.2 SNK test on the effect of scene complexity on nausea

SNK Grouping	Mean	N	scene complexity
A	2.0476	84	high
B	0.9167	84	median
C	0.2262	84	low

(Note that means with the same letter are not significantly different)

Table R.3 SNK test on the effect of duration on nausea ratings

SNK Grouping			Mean	N	Duration (minutes)
	A		2.0556	36	30
	A				
B	A		1.7500	36	25
B	A				
B	A	C	1.4167	36	20
B		C			
B		C	1.1389	36	15
		C			
	D	C	0.8333	36	10
	D				
E	D		0.2500	36	5
E					
E			0.0000	36	0

(Note that means with the same letter are not significantly different)

Table R.4a ANOVA result on the effect of duration on nausea ratings of each condition individually (3 conditions)

High scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (minutes)	6	126.142857	21.023810	4.66	0.0004*
Error	77	347.666667	4.515152		
Medium scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (duration)	6	38.6666667	6.4444444	4.21	0.0010*
Error	77	117.7500000	1.5292208		
Low scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (minutes)	6	4.28571429	0.71428571	5.28	0.0001*
Error	77	10.41666667	0.13528139		

(Note that * indicate a significant effect at p=0.05)

Table R.4b. SNK test on the effect of duration on nausea ratings of each condition individually (3 conditions)

High scene complexity

SNK Grouping			Mean	N	Duration (minutes)
	A		3.5833	12	30
	A				
	A		3.2500	12	25
	A				
B	A		2.6667	12	20
B	A				
B	A		2.4167	12	15
B	A				
B	A	C	1.7500	12	10
B		C			
B		C	0.6667	12	5
		C			
		C	0.0000	12	0

Medium scene complexity

SNK Grouping		Mean	N	Duration (minutes)
	A	1.9167	12	30
	A			
	A	1.5833	12	25
	A			
B	A	1.3333	12	20
B	A			
B	A	0.8333	12	15
B	A			
B	A	0.6667	12	10
B				
B		0.0833	12	5
B				
B		0.0000	12	0

Low scene complexity

SNK Grouping		Mean	N	Duration (minutes)	
	A	0.6667	12	30	A
B	A	0.4167	12	25	
B					
B		0.2500	12	20	
B					
B		0.1667	12	15	
B					
B		0.0833	12	10	
B					
B		0.0000	12	5	
B		0.0000	12	0	

(Note that means with the same letter are not significantly different)

Table R.5 ANOVA result for apparent self-motion ratings in 3 different scene complexity conditions

Source	DF	SS	Mean Square	F Value	Pr > F
Scene complexity	2	58.5000000	29.2500000	61.71	0.0001*
Duration	6	26.6507937	4.4417989	9.37	0.0001*
Scene complexity * Duration	12	14.7777778	1.2314815	2.60	0.0029*
Error	231	109.5000000	0.4740260		

(Note that * indicate a significant effect at p=0.05)

Table R.6 SNK test on the effect of scene complexity on apparent self-motion ratings

SNK Grouping	Mean	N	Scene complexity
A	1.2976	84	high
B	0.3333	84	median
B			
B	0.2262	84	low

(Note that means with the same letter are not significantly different)

Table R.7 SNK test on the effect of duration on apparent self-motion ratings

SNK Grouping		Mean	N	Duration (minutes)
	A	1.0000	36	30
	A			
	A	0.9167	36	25
	A			
	A	0.8056	36	20
	A			
B	A	0.6944	36	15
B	A			
B	A	0.5833	36	10
B				
B		0.3333	36	5
	C	0.0000	36	0

(Note that means with the same letter are not significantly different)

Table R.8a. ANOVA result on the effect of duration on apparent self-motion ratings of each condition individually (3 conditions)

High scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (duration)	6	36.4761905	6.0793651	7.19	0.0001*
Error	77	65.0833333	0.8452381		
Medium scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	6	3.16666667	0.52777778	1.29	0.2718
Error	77	31.50000000	0.40909091		
Low scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (duration)	6	1.78571429	0.29761905	1.77	0.1155
Error	77	12.91666667	0.16774892		

(Note that * indicate a significant effect at p=0.05)

Table R.8b SNK test on the effect of duration on apparent self-motion ratings of each condition individually (3 conditions)

High scene complexity

SNK Grouping		Mean	N	Duration (minutes)
	A	2.0000	12	30
	A			
	A	1.9167	12	25
	A			
B	A	1.6667	12	20
B	A			
B	A	1.5000	12	15
B	A			
B	A	1.2500	12	10
B				
B		0.7500	12	5
C		0.0000	12	0

Medium scene complexity

SNK Grouping	Mean	N	Duration (minutes)
A	0.5000	12	20
A			
A	0.5000	12	25
A			
A	0.5000	12	30
A			
A	0.4167	12	15
A			
A	0.3333	12	10
A			
A	0.0833	12	5
A			
A	0.0000	12	0

Low scene complexity

SNK Grouping	Mean	N	Duration (minutes)
A	0.5000	12	30
A			
A	0.3333	12	25
A			
A	0.2500	12	20
A			
A	0.1667	12	15
A			
A	0.1667	12	10
A			
A	0.1667	12	5
A	0.0000	12	0

(Note that means with the same letter are not significantly different)

Table R.9 The descriptive statistics of the pre, post and change sickness score (Nausea, Oculomotor, Disorientation, Total sickness score)

		Nausea	sub-score	
Scene complexity	Times	N	Mean	SD
high	Post	12	51.675	39.3256623
high	Pre	12	0.795	2.7539608
high	Change	12	50.88	40.1326491
low	Post	12	7.155	10.0674638
low	Pre	12	0.795	2.7539608
low	Change	12	6.36	8.467946
median	Post	12	23.85	30.3049465
median	Pre	12	0.795	2.7539608
median	Change	12	23.055	30.0192061
		Oculomotor	sub-score	
Scene complexity	Times	N	Mean	SD
high	Post	12	34.11	24.5087851
high	Pre	12	3.79	6.856368
high	Change	12	30.32	19.9241434
low	Post	12	8.8433333	8.4489777
low	Pre	12	1.2633333	2.950511
low	Change	12	7.58	7.9170518
median	Post	12	29.6883333	27.1302655
median	Pre	12	4.4216667	6.0106479
median	Change	12	25.2666667	28.0531383
		Disorientation	sub-score	
Scene complexity	Times	N	Mean	SD
high	Post	12	42.92	32.7575157
high	Pre	12	2.32	5.4183527
high	Change	12	40.6	31.102477
low	Post	12	2.32	5.4183527
low	Pre	12	0	0
low	Change	12	2.32	5.4183527
	Total	sickness	score	
Scene complexity	Times	N	Mean	SD
high	Post	12	48.62	34.6833332
high	Pre	12	2.805	5.0744359
high	Change	12	45.815	32.2565761
low	Post	12	7.7916667	9.0855948
low	Pre	12	0.935	2.324715
low	Change	12	6.8566667	8.1055125
median	Post	12	31.1666667	35.0238509
median	Pre	12	2.805	3.9467835
median	Change	12	28.3616667	35.3535972

Table R.10. ANOVA result on Nausea sub-score of pre immersion profiles

Source	DF	SS	Mean Square	F Value	Pr > F
Scene complexity	2	0.000000	0.000000	0.00	1.0000
Error	33	250.281900	7.584300		

Table R.11. ANOVA result on Oculomotor sub-score of pre immersion profiles

Source	DF	SS	Mean Square	F Value	Pr > F
Scene complexity	2	67.0324667	33.5162333	1.09	0.3465
Error	33	1010.2750333	30.6143949		

Table R.12. ANOVA result on Disorientation sub-score of pre immersion profiles

Source	DF	SS	Mean Square	F Value	Pr > F
Scene complexity	2	32.2944000	16.1472000	1.06	0.3564
Error	33	500.5632000	15.1685818		

Table R.13. ANOVA result on Total Sickness score of pre immersion profiles

Source	DF	SS	Mean Square	F Value	Pr > F
Scene complexity	2	27.9752000	13.9876000	0.90	0.4171
Error	33	514.0443000	15.5771000		

Table R.14. ANOVA result on Nausea sub-score (comparison between pre and post- immersion profiles of each condition individually)

High scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (time)	1	15532.6464	15532.6464	19.99	0.0002*
Error	22	17095.0122	777.0460		
Medium scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (time)	1	3189.19815	3189.19815	6.89	0.0155*
Error	22	10185.71490	462.98704		
Low scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (time)	1	242.697600	242.697600	4.46	0.0464*
Error	22	1198.319400	54.469064		

(Note that * indicate a significant effect at p=0.05)

Table R.15. ANOVA result on Oculomotor sub-score (comparison between pre and post- immersion profiles)

Source	DF	SS	Mean Square	F Value	Pr > F
High scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (time)	1	5515.81440	5515.81440	17.03	0.0004*
Error	22	7124.59360	323.84516		
Medium scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model	1	3830.42667	3830.42667	9.92	0.0047*
Error	22	8493.97113	386.08960		
Low scene complexity					
Source	DF	SS	Square	F Value	Pr > F
Model (time)	1	344.738400	344.738400	8.61	0.0077*
Error	22	880.998133	40.045370		

(Note that * indicate a significant effect at p=0.05)

Table R.16. ANOVA result on Disorientation sub-score (comparison between pre and post- immersion profiles)

Source	DF	SS	Mean Square	F Value	Pr > F
High scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (time)	1	9890.16000	9890.16000	17.94	0.0003*
Error	22	12126.54720	551.20669		
Medium scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (time)	1	3907.62240	3907.62240	5.05	0.0350*
Error	22	17019.14880	773.59767		
Low scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (time)	1	32.2944000	32.2944000	2.20	0.1522
Error	22	322.9440000	14.6792727		

(Note that * indicate a significant effect at p=0.05)

Table R.17. ANOVA result on Total Sickness score (comparison between pre and post- immersion profiles)

High scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (time)	1	12594.0854	12594.0854	20.50	0.0002*
Error	22	13515.5185	614.3417		
Medium scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (time)	1	4826.30482	4826.30482	7.77	0.0107*
Error	22	13664.71957	621.12362		
Low scene complexity					
Source	DF	SS	Mean Square	F Value	Pr > F
Model (time)	1	282.083267	282.083267	6.41	0.0190*
Error	22	967.475667	43.976167		

(Note that * indicate a significant effect at p=0.05)

Table R.18 ANOVA result for Nausea sub-score of the change sickness profiles in 3 different scene complexity conditions

Source	DF	SS	Mean Square	F Value	Pr > F
Scene complexity	2	12139.9362	6069.9681	7.05	0.0028*
Error	33	28418.3721	861.1628		

(Note that * indicate a significant effect at p=0.05)

Table R.19 ANOVA result for Oculomotor sub-score of the change sickness profiles in 3 different scene complexity conditions

Source	DF	SS	Mean Square	F Value	Pr > F
Scene complexity	2	3421.84782	1710.92391	4.12	0.0253*
Error	33	13712.92747	415.54326		

(Note that * indicate a significant effect at p=0.05)

Table R.20 ANOVA result for Disorientation sub-score of the change sickness profiles in 3 different scene complexity conditions

Source	DF	SS	Mean Square	F Value	Pr > F
Scene complexity	2	8924.01920	4462.00960	5.20	0.0109*
Error	33	28338.33600	858.73745		

(Note that * indicate a significant effect at p=0.05)

Table R.21 ANOVA result for Total sickness score of the change sickness profiles in 3 different scene complexity conditions

Source	DF	SS	Mean Square	F Value	Pr > F
Scene complexity	2	9139.34242	4569.67121	5.82	0.0068*
Error	33	25916.69153	785.35429		

(Note that * indicate a significant effect at p=0.05)

Table R.22 SNK test on the effect of scene complexity on Nausea sub-score of the 3 conditions

SNK Grouping	Mean	N	scene complexity
A	50.88	12	high
B	23.06	12	median
B			
B	6.36	12	low

(Note that means with the same letter are not significantly different)

Table R.23 SNK test on the effect of scene complexity on Oculomotor sub-score of the 3 conditions

SNK Grouping	Mean	N	scene complexity
A	30.320	12	high
A			
A	25.267	12	median
B	7.580	12	low

(Note that means with the same letter are not significantly different)

Table R.24 SNK test on the effect of scene complexity on Disorientation sub-score of the 3 conditions

SNK Grouping	Mean	N	scene ocmplexity
A	40.60	12	high
A			
B A	25.52	12	median
B			
B	2.32	12	low

(Note that means with the same letter are not significantly different)

Table R.25 SNK test on the effect of scene complexity on Total sickness score of the 3 conditions

SNK Grouping		Mean	N	Scene complexity
	A	45.82	12	high
	A			
B	A	28.36	12	median
B				
B		6.86	12	low

(Note that means with the same letter are not significantly different)

Table R.26 ANOVA result for Q1 to Q6 of simulation assessment question

Source	DF	SS	Mean Square	F Value	Pr > F
Q1: Did you feel you were moving during the experiment?					
Scene complexity	2	14.2222222	7.1111111	10.83	0.0002*
Error	33	21.6666667	0.6565657		
Q2: How uncomforted of HMD?					
Scene complexity	2	1.72222222	0.86111111	1.34	0.2764
Error	33	21.25000000	0.64393939		
Q3: How completely did you believe you were part of virtual environment?					
Scene complexity	2	15.1666667	7.5833333	11.59	0.0002*
Error	33	21.5833333	0.6540404		
Q4: How flat and missing in depth did the world appear?					
Scene complexity	2	8.66666667	4.33333333	6.48	0.0042*
Error	33	22.08333333	0.66919192		
Q5: How excited do you feel after the experiment?					
Scene complexity	2	5.05555556	2.52777778	3.59	0.0389*
Error	33	23.25000000	0.70454545		
Q6: How real was the graph simulation?					
Scene complexity	2	30.3888889	15.1944444	47.75	0.0001*
Error	33	10.5000000	0.3181818		

(Note that * indicate a significant effect at p=0.05)

Table R.27 SNK test on the effect of scene complexity on Q1 to Q6 of the simulation assessment questionnaire

SNK Grouping		Mean	N	scene complexity
Q1: Did you feel you were moving during the experiment?				
SNK Grouping		Mean	N	scene complexity
	A	1.8333	12	high
	B	0.5000	12	low
	B			
	B	0.5000	12	median
Q2: How uncomforted of HMD?				
SNK Grouping		Mean	N	scene complexity
	A	1.6667	12	low
	A			
	A	1.5833	12	high
	A			
	A	1.1667	12	median
Q3: How completely did you believe you were part of virtual environment?				
SNK Grouping		Mean	N	scene complexity
	A	2.3333	12	high
	B	1.0000	12	median
	B			
	B	0.9167	12	low
Q4: How flat and missing in depth did the world appear?				
SNK Grouping		Mean	N	scene complexity
	A	2.4167	12	low
	A			
	A	2.0833	12	median
	B	1.2500	12	high
Q5: How excited do you feel after the experiment?				
SNK Grouping		Mean	N	scene complexity
	A	1.3333	12	high
	A			
B	A	0.8333	12	median
B				
B		0.4167	12	low
Q6: How real was the graph simulation?				
SNK Grouping		Mean	N	scene complexity
	A	2.6667	12	high
	B	1.5833	12	median
	C	0.4167	12	low

(Note that means with the same letter are not significantly different)

Table R.28 Correlation coefficients with the p values of 6 questions of the simulation assessment form with the nausea & apparent self-motion ratings at 30 minutes

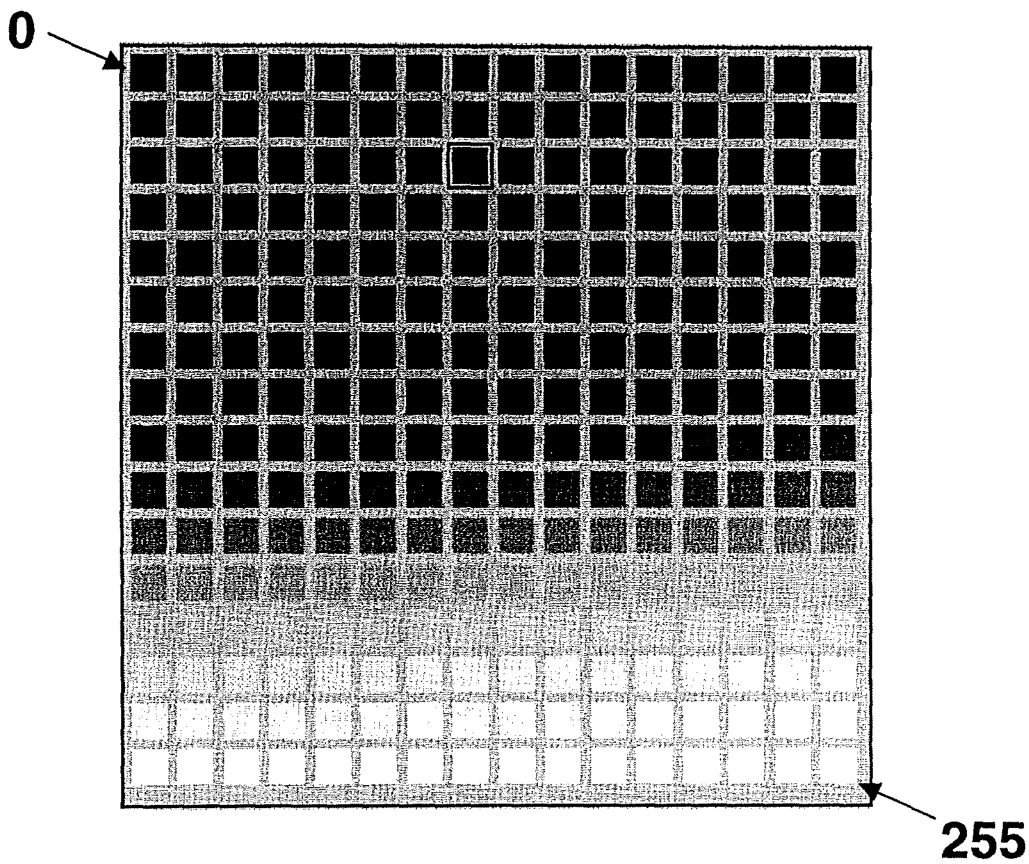
	Ql	Q2	Q3	Q4	Q5	Q6	Nausea ratings	Apparent self-motion ratings
Q1	1							
	0							
Q2	0.10401	1						
	0.5521	0						
Q3	0.52053	0.09412	1					
	0.0013	0.5907	0					
Q4	-0.33634	0.13074	-0.43883	1				
	0.0482	0.4541	0.0084	0				
Q5	0.39907	-0.14081	0.62628	-0.42147	1			
	0.0176	0.4198	0.0001	0.0117	0			
Q6	0.51722	-0.17596	0.66712	-0.58791	0.60685	1		
	0.0015	0.312	0.0001	0.0002	0.0001	0		
Nausea ratings	0.8326	0.02727	0.40023	-0.31534	0.37132	0.51962	1	
	0.0001	0.8764	0.0172	0.065	0.0281	0.0014	0	
Apparent self-motion ratings	0.90764	0.04990	0.48814	0.34916	0.35713	0.5325	0.85181	1
	0.0001	0.7759	0.0029	0.0598	0.0352	0.001	0.0001	0

Q1: Did you feel you were moving during the experiment?, Q2: How uncomforted of HMD?, Q3: How completely did you believe you were part of virtual environment?, Q4: How flat and missing in depth did the world appear?, Q5: How excited do you feel after the experiment?, Q6: How real was the graph simulation?

Appendix S

This appendix illustrates the full range of gray scale values (0-255). Chapter 4 (Method to quantify scene content in virtual environment) is related to this appendix.

The full range of gray scale values (0-255)



Appendix T

This appendix illustrates the method and steps to calculate the spatial frequencies of a dynamic virtual environment. Chapter 4 (Method to quantify scene content in virtual environment) is related to this appendix.

Method to calculate the spatial frequencies of a dynamic virtual environment.

Step 1: Take five representative snapshots of the dynamic virtual environment

For the ease of explanation, the pictures have been assigned as Picture I, Picture II, Picture III, Picture IV and Picture V.

Step 2: Gray scale extraction

The spatial frequencies of the five captured pictures will be calculated individually. First, it is necessary to store the pictures in a format that containing the gray scale information of each pixel of the pictures. The gray scales of each pixel are then extracted. The gray scale of each pixel is an indication of the luminance level of that pixel. In addition, the information is stored in ASCII format. A file format called – portable graymap file format 'pgm' is used (steps to store a picture in 'pgm' format in an Onyx workstation is shown in Appendix H)

A C++ program (see Appendix I) has been developed to extract the gray scale of each pixel of the pictures.

Step 3: Edge elimination

Before calculating the spatial frequencies of the pictures, the edges of the pictures should be eliminated first. As some back lines in the edges of the picture may be introduced during the procedure of capturing a picture. These black lines could affect the values of spatial frequencies. By trial and error, the width of the black lines are usually less than 3 pixels, so it is appropriate to cut 1% pixels in top, bottom, left and right sides of the picture and rescale the corresponding FOV respectively. For example, a picture with dimension 640 (horizontal) × 480 (vertical) pixels and the field of view is 48° (horizontal) × 36° (vertical), the new dimensions and the corresponding FOV after the elimination are 627 (horizontal) × 470 (vertical) pixels and 47° (horizontal) × 35° (vertical) respectively.

Step 4: Extract the gray scale values of pixel within each row

Treating the gray scales values of each row as a series of numbers

Step 5: Calculate Power Spectral density of a row

After extraction of the gray scale series of each row, it is necessary to calculate the Power Spectral Density (PSD) of these gray scale series. The calculation of the PSD distribution will involve the use of Fast Fourier Transformation (FFT). The PSD distribution graph will indicate the dominant frequencies of the gray scale series. Within a gray scale series there may be several dominant frequencies (showing peaks in the PSD graph). The meaning of the dominant frequencies in this study is satisfying the two following conditions at the same time: (i) greater than a threshold value, 1000, the hypothesis is that below that threshold value, human cannot perceive the luminance level changes. Further investigation of it is desirable; and (ii) frequencies at which the PSD graph shows peak values greater than half of the value of the highest peak occurs in the PSD distribution. After the dominant frequencies have been identified, the average value would be used to represent the average frequency of the particular row. As a result, the following equation (Equation T.1) could be used to describe how to obtain the average frequency of each row:

$$\begin{pmatrix}\text{average frequency of the row,}\\ F_{ave(i)}\ (i : \text{ith row})\end{pmatrix} = \frac{\sum\begin{pmatrix}\text{the value of the peak at which the PSD graph}\\ \text{has a peak value} > \text{threshold value} : 1000\ \&\\ \text{half of the value of the max. peak}\end{pmatrix}}{\begin{pmatrix}\text{Total number of peaks which are} > \text{the threshold}\\ \text{value} : 1000\ \&\ \text{the half of the value of the max.peak}\end{pmatrix}}$$

Equation T.1

Step 6: Calculate the average spatial frequency of a row

Dividing the average frequency of the row by the horizontal field of view, the average spatial frequency of the row is obtained (see Equation T.2).

$$\begin{pmatrix}\text{average spatial frequency} \\ \text{of the row, } SF_{row(i)}\,(i:\text{ith}:\text{row})\end{pmatrix} = \frac{F_{ave(i)}}{\text{horizontal FOV}}$$

Equation T.2

Step 7: Calculate the average spatial frequencies of all rows

The same procedures are repeated to calculate all average spatial frequencies of all rows.

Step 8: Calculate the average horizontal spatial frequency of one picture

The average horizontal spatial frequencies of Picture I ($SF_{horizontal\text{-}Picture\ I}$) is the average of the values of the spatial frequencies of the rows (see Equation T.3)

$$\begin{pmatrix}\text{average horizontal spatial frequency} \\ \text{of Picture I, } SF_{horizontal\text{ - }picture\ I}\end{pmatrix} = \frac{\sum_{i=1\,st\,row}^{n=last\,row} SF_{row(i)}}{\text{total number of rows}}$$

Equation T.3

Step 9: Extract the gray scale values of pixel within each column

Treating the gray scales values of each column as a series of numbers.

Step 10: Calculate the Power Spectral density of a column

The same method is applied to calculate the average frequency of a column.

$$\begin{pmatrix}\text{average frequency of the column,}\\ F_{ave(j)}\ (j:\text{jth column})\end{pmatrix}=\frac{\sum\begin{pmatrix}\text{the value of the peak at which the PSD graph}\\ \text{has a peak value} > \text{threshold value}: 1000\ \&\\ \text{half of the value of the max. peak}\end{pmatrix}}{\begin{pmatrix}\text{Total number of peaks which are} > \text{the threshold}\\ \text{value}: 1000\ \&\ \text{the half of the value of the max.peak}\end{pmatrix}}$$

Equation T.4

Step 11: Calculate the average spatial frequency of a column

$$\begin{pmatrix}\text{average spatial frequency}\\ \text{of the column, } SF_{column(j)}\ (j:\text{jth}:\text{column})\end{pmatrix}=\frac{F_{ave(j)}}{\text{vertical FOV}}$$

Equation T.5

Step 12: Calculate the average spatial frequencies of all columns

Repeat the same calculating procedures to calculate all the average spatial frequencies of all columns.

Step 13 Calculate the average vertical spatial frequency of a picture

$$\begin{pmatrix}\text{average vertical spatial frequency} \\ \text{of Picture I, } SF_{\text{vertical - picture I}}\end{pmatrix} = \frac{\sum_{i=1\text{st column}}^{n=\text{last column}} SF_{\text{column(j)}}}{\text{total number of columns}}$$

Equation T.6

Step 14: Calculate the average radial spatial frequency of a picture

Besides, the radial spatial frequency of Picture I ($SF_{\text{radial-Picture I}}$) is calculated by Equation T.7

$$\begin{pmatrix}\text{average radial spatia frequency} \\ \text{of Picture I, } SF_{\text{radial - Picure I}}\end{pmatrix} = \sqrt{SF_{\text{horizontal - Picture I}}^{2} + SF_{\text{vertical - Picture I}}^{2}}$$

Equation T.7

Step 15: Calculate the average horizontal, vertical and radial spatial frequencies of all pictures

Similarly, the average horizontal, vertical and radial frequencies of Picture II, Picture III, Picture IV and Picture V can be obtained by the same method.

Step 16 Calculate the average horizontal, vertical and radial spatial frequencies of the dynamics virtual environment

Finally, the average values of these five pictures can be used to represent the three axes spatial frequencies of the dynamic virtual environment simulation.

$$\begin{pmatrix}\text{average horizontal spatial frequency} \\ \text{of an virtual environment, } SF_{\text{horizontal}}\end{pmatrix} = \frac{\sum_{k=I}^{V} SF_{\text{horizontal - Picture (k)}}}{\text{total number of pictures}}$$

Equation T.8

$$\begin{pmatrix}\text{average vertical spatial frequency} \\ \text{of an virtual environment, } SF_{\text{vertical}}\end{pmatrix} = \frac{\sum_{k=I}^{V} SF_{\text{vertical - Picture (k)}}}{\text{total number of pictures}}$$

Equation T.9

$$\begin{pmatrix}\text{average radial spatial frequency} \\ \text{of an virtual environment, } SF_{radial}\end{pmatrix} = \frac{\sum_{k=1}^{V} SF_{radial - Picture\,(k)}}{\text{total number of pictures}}$$

Equation T.10

The spatial frequencies of the virtual environment represent the luminance level changes spatially over the whole simulation.

Appendix U

The normal probability plots of nausea ratings, Nausea sub-score, Oculomotor sub-score, Disorientation sub-score and Total Sickness (TS) score of experiment 1.

Chapter 7 (Studies of effects of scene rotation axes on cybersickness with a head-coupled virtual reality system is related to this appendix.

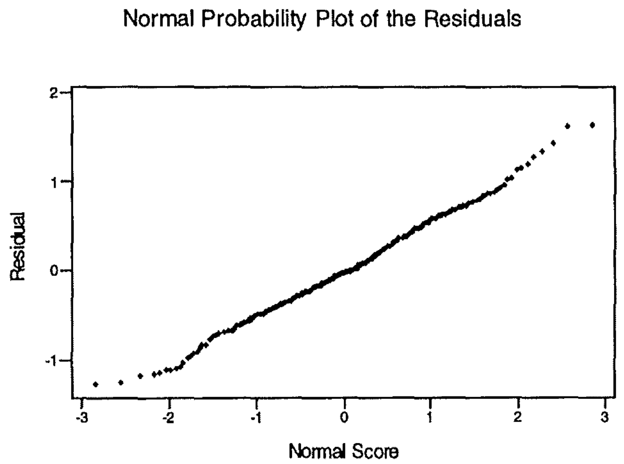


Figure U.1 Normal probability plot of nausea ratings of experiment 1 (effects of rotation axes on cybersickness)

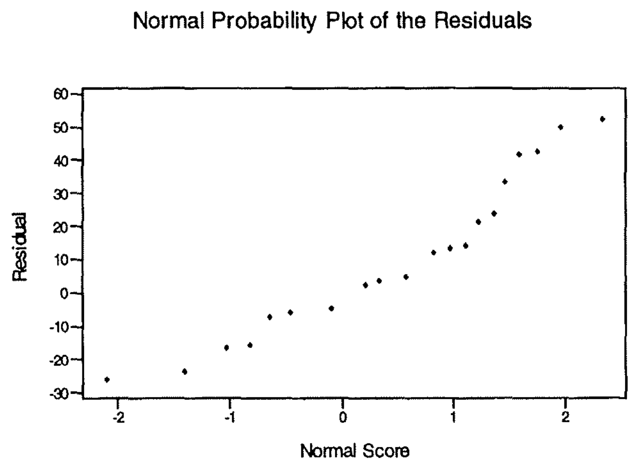


Figure U.2 Normal probability plot of Nausea sub-score of experiment 1 (effects of rotation axes on cybersickness)

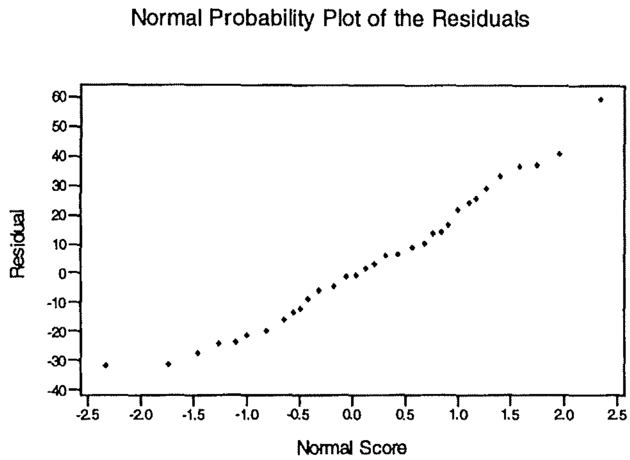


Figure U.3 Normal probability plot of Oculomotor sub-score of experiment 1 (effects of rotation axes on cybersickness)

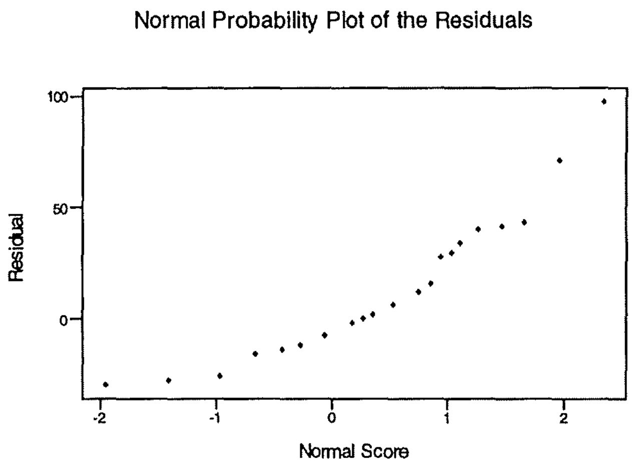


Figure U.4 Normal probability plot of Disorientation sub-score of experiment 1 (effects of rotation axes on cybersickness)

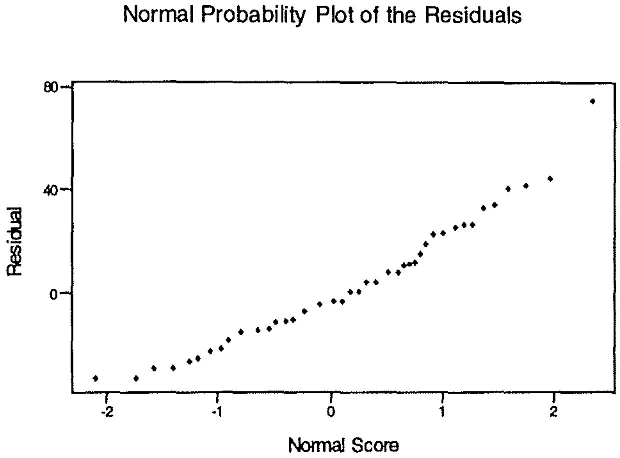


Figure U.5 Normal probability plot of Total Sickness score of experiment 1 (effects of rotation axes on cybersickness)

Appendix V

The normal probability plots of nausea ratings, apparent self-motion ratings, Nausea sub-score, Oculomotor sub-score, Disorientation sub-score and Total Sickness (TS) scores of experiment 2.

Chapter 8 (Studies of effects of visual scene velocity on cybersickness with a head-coupled virtual reality system) is related to this appendix.

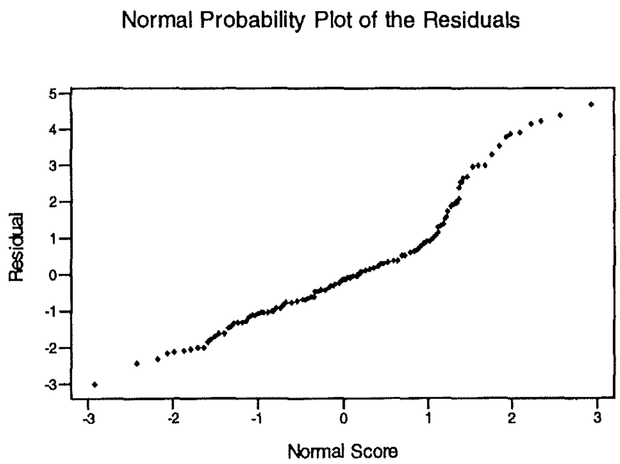


Figure V.1 Normal probability plot of nausea ratings of experiment 2 (effects of scene velocity on cybersickness)

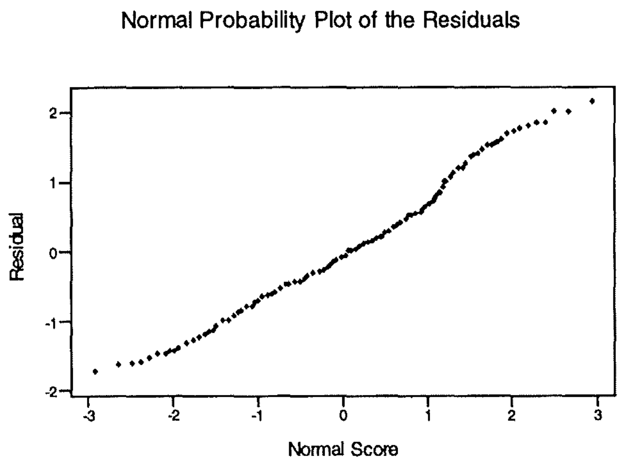


Figure V.2 Normal probability plot of apparent self-motion ratings of experiment 2 (effects of scene velocity on cybersickness)

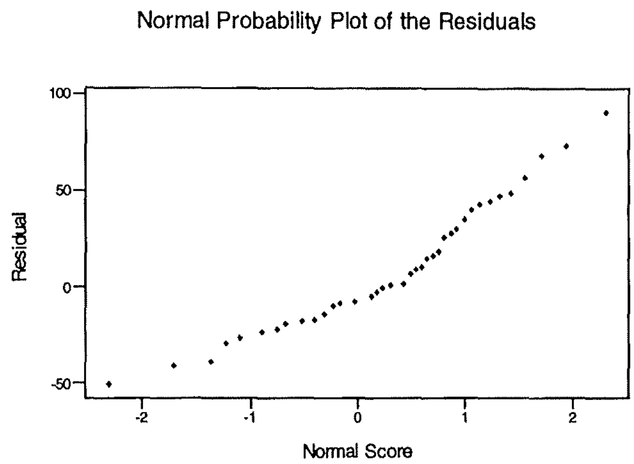


Figure V.3 Normal probability plot of Nausea sub-score of experiment 2 (effects of scene velocity on cybersickness)

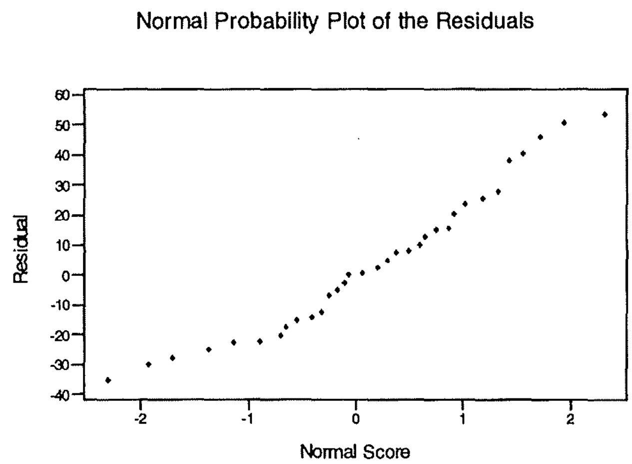


Figure V.4 Normal probability plot of Oculomotor sub-score of experiment 2 (effects of scene velocity on cybersickness)

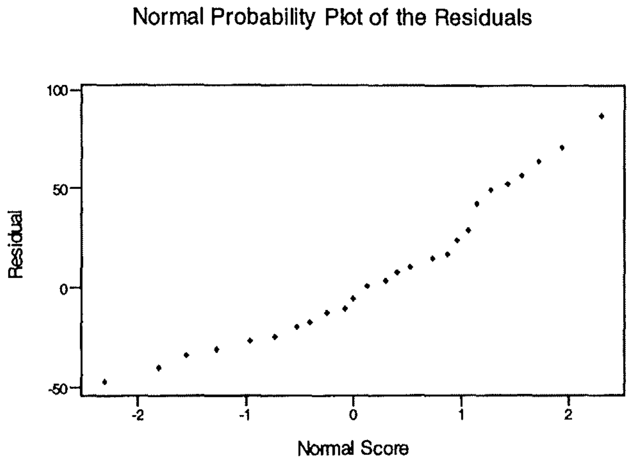


Figure V.5 Normal probability plot of Disorientation sub-score of experiment 2 (effects of scene velocity on cybersickness)

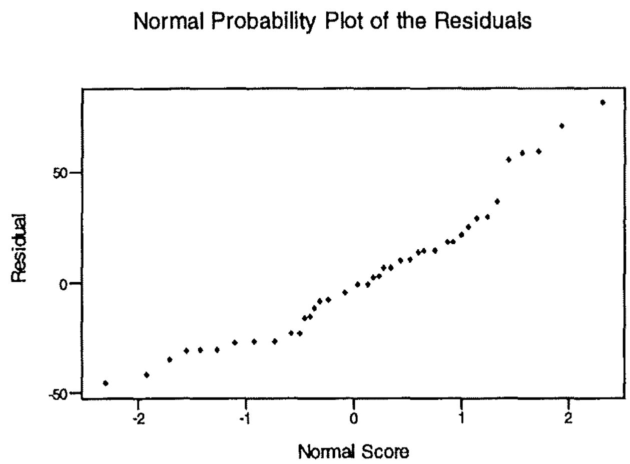


Figure V.6 Normal probability plot of Total Sickness score of experiment 2 (effects of scene velocity on cybersickness)

Appendix W

The normal probability plots of nausea ratings, apparent self-motion ratings, Nausea sub-score, Oculomotor sub-score, Disorientation sub-score and Total Sickness (TS) scores of experiment 3.

Chapter 9 (Studies of effects of scene complexity on cybersickness with a head-coupled virtual reality system) is related to this appendix.

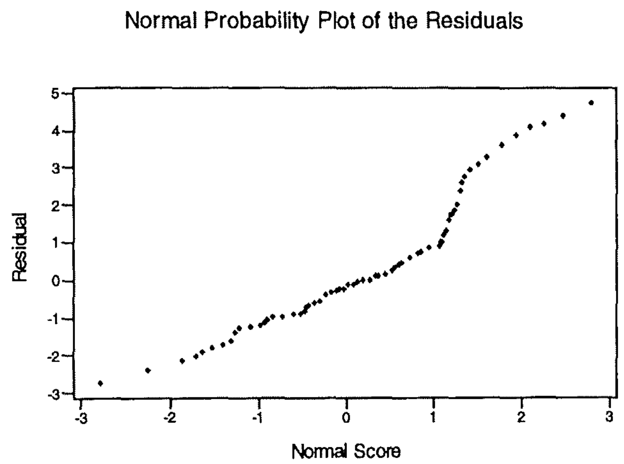


Figure W.1 Normal probability plot of nausea ratings of experiment 3 (effects of scene complexity on cybersickness)

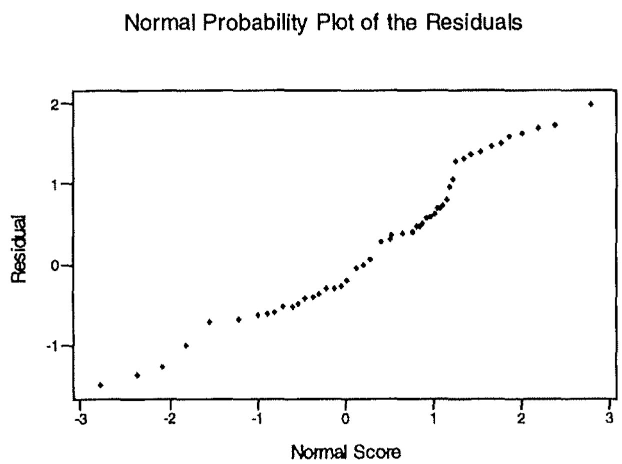


Figure W.2 Normal probability plot of apparent self-motion ratings of experiment 3 (effects of scene complexity on cybersickness)

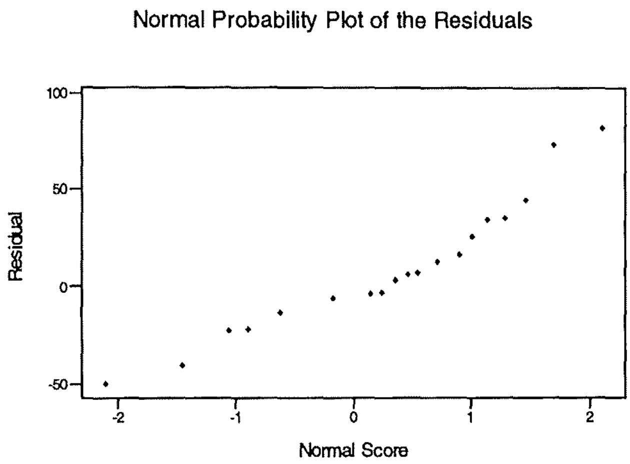


Figure W.3 Normal probability plot of Nausea sub-score of experiment 3 (effects of scene complexity on cybersickness)

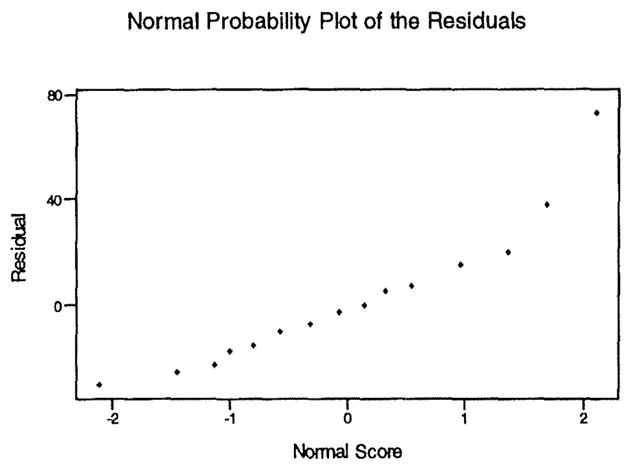


Figure W.4 Normal probability plot of Oculomotor sub-score of experiment 3 (effects of scene complexity on cybersickness)

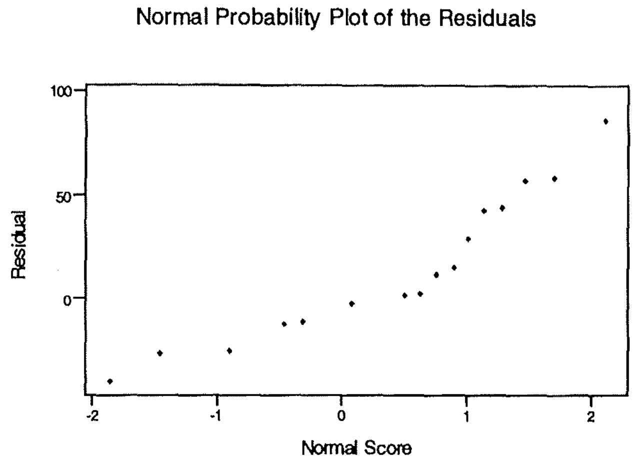


Figure W.5 Normal probability plot of Disorientation sub-score of experiment 3 (effects of scene complexity on cybersickness)

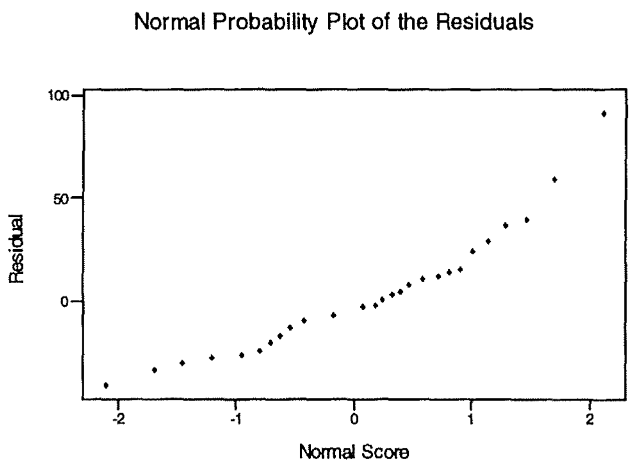


Figure W.6 Normal probability plot of Total Sickness score of experiment 3 (effects of scene complexity on cybersickness)

~ End ~