Effects of scene complexity in Virtual Environments on the levels of cybersickness

by

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

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Abstract

Users of virtual reality (VR) systems can experience cybersickness. This phenomenon has been referred to as visually-induced motion sickness and hence scene complexity should play an important role in causing this problem. A previous study quantified scene complexity using 'spatial frequency' (unit: cycles per degree, cpd) but did not thoroughly study its relationship with cybersickness. Also, the effect of color was assumed to be negligible.

The purpose of this thesis was to investigate the effects of spatial frequency and color of virtual environments (VEs) on cybersickness. In addition, the method of quantifying scene complexity with spatial frequency was optimized. Two experiments with 144 participants were conducted. Experimental results showed that levels of cybersickness significantly increase with increasing spatial frequency until 0.076cpd ($p<0.05$). Beyond a spatial frequency of 0.076cpd, the levels of cybersickness remained steady even when the spatial frequency increased to 0.413cpd. Color, on the other hand, did not show any

significant effect on the levels of cybersickness ($p>0.4$). This verified the previous assumption that the color of a VE did not affect the associated cybersickness. An algorithm was developed to determine the optimal number of pictures to be randomly captured during a VR simulation in order to estimate the average spatial frequency of that simulation. This algorithm has been shown to reduce the number of pictures needed to be captured during a 30-minute VR simulation session from 3600 to below 60.

The experimental findings are anchored with the past literature concerning visually-induced motion sickness with rotating drums. In particular, the consistency among the findings, the two visual systems theory, and the past findings with rotating drums are discussed.

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Chapter 1. Introduction

1.1. Development and Applications of Virtual Reality Systems

Virtual reality is a computer-generated environment. This technology has been widely used for decades. It allows people to simulate different real world situations. With the advancements in computation power of computers, more realistic and complicated virtual environments are now being developed. Moreover, with equipment like head-mounted displays (Figure 1.1) and Cyberglove™, with position trackers attached for updating positions in the virtual world, users of virtual reality systems can experience more immersion and interaction within the virtual environment.

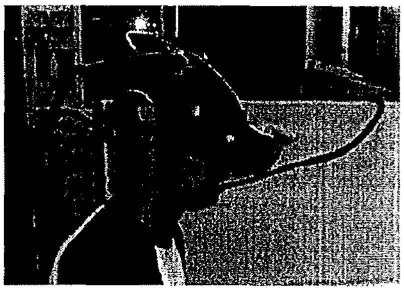


Figure 1.1 Head-mounted Display

Virtual reality systems have been applied in many areas such as training and entertainment. The US Air Force, for example, has been using flight simulators to train their pilots. Virtual reality technology is used to simulate flights and missions in flight simulators. Different scenarios can be generated in order to train the pilots to deal with different situations, including emergencies. Such training can ensure the pilots are well trained and familiar with the operation of the planes. Since pilots do not need to take real flights for training, the training cost and time can be reduced.

Entertainment is another popular virtual reality application area. Many video games use this technology to become more realistic and interactive. This creates more stimulation and enjoyment for the players. Education is also making use of more and more virtual reality technology. . 3-dimensional objects and scenery can give learners a clearer picture of their topic. This makes the learning process more interactive and effective.

1.2. Cybersickness and its relationship with scene complexity

Although virtual reality can create a compelling, realistic and interactive environment, there is a drawback with using virtual reality systems. Many researchers have discovered that users of virtual reality systems can suffer from symptoms of motion sickness, defined as cybersickness by McCauley and Sharkey (1992), during and after exposure to the virtual environment. This may affect the development of virtual reality because cybersickness may decrease the willingness of people to use this technology. Even worse, users may face potential risks after using virtual reality systems, as they could have various symptoms due to cybersickness. The awful experience would also decrease the knowledge transfer to learners during training.

Previous studies have shown that cybersickness is a visually induced motion sickness (Hettinger & Riccio, 1992), i.e. the visual stimuli seen by the users of virtual reality systems are an important driver of cybersickness. Therefore, the content in the visual scenes should play an important role in how severely cybersickness affects the users of virtual reality systems. The degree of complication for the content in the virtual environments is defined as scene complexity in this thesis. There are many attributes related to scene complexity such as color and spatial frequency. Details will be discussed in Chapter 3. Previous studies from Lo (1998) and So et al. (2001) found that certain components of scene complexity in virtual environments have significant effects on the levels of cybersickness. Their results showed that the higher the spatial frequency, the higher the levels of cybersickness experienced by the users of virtual reality systems.

1.3. Purpose of the research

This research aims at studying the effects of scene complexity in virtual environment on the levels of cybersickness.

The specific objectives are:

(i) To optimize the method of quantifying the scene complexity in virtual environments

(ii) To study the effects of different color with similar spatial frequency on the levels of cybersickness

(iii) To study the effects of different levels of spatial frequency on the levels of cybersickness

  a. Using another virtual environment to compare with the results from previous studies

  b. Extend the range of scene complexity to study the effect of extremity

1.4. Organization of the thesis

The outline of the thesis is illustrated in Figure 1.2.

Chapter 1 to 3 gives some background information about this research. Chapter 1 introduces virtual reality technology and cybersickness. Chapter 2 reviews the literature on measurements and possible causes of cybersickness. Chapter 3 reviews the literature on the two attributes of scene complexity, color and spatial frequency. The related literatures on visually-induced motion sickness are presented too.

Chapters 4 to 8 present the work done for this research. Chapter 4 is the optimization work for the method of quantifying scene complexity in virtual environments. Chapter 5 is the experimental work on the effects of color with similar spatial frequency on levels of cybersickness. Chapter 6 is the experimental work on the effects of different spatial frequency on levels of cybersickness. Chapters 7 and 8 are the overall discussion, conclusion, limitations and some suggestions on future work.

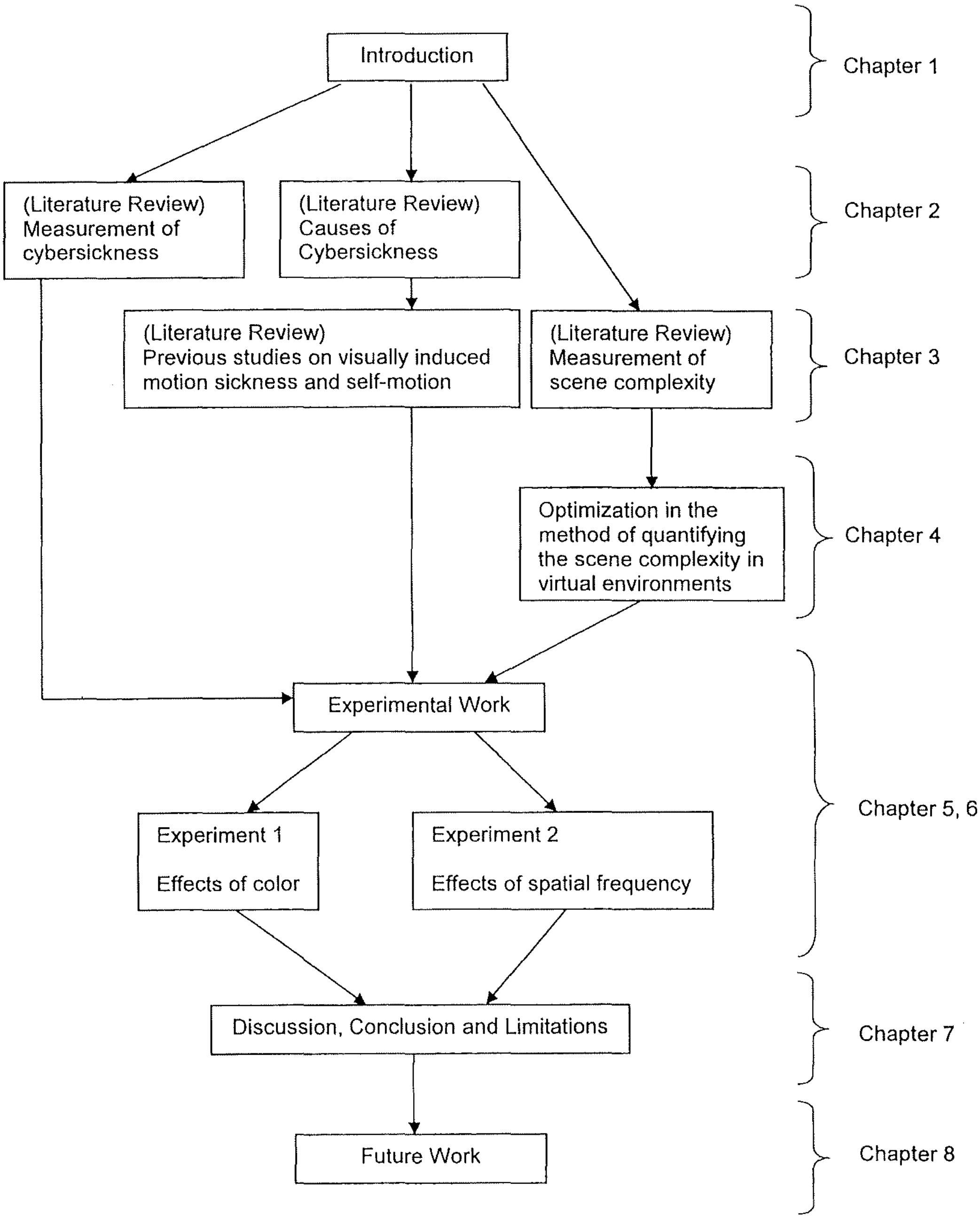


Figure 1.2 Outline of the thesis

Chapter 2. Literature Review on Cybersickness

2.1. Cybersickness: definition and methods of measurement

2.1.1. Definition

McCauley and Sharkey (1992) defined the motion sickness associated with virtual reality systems as cybersickness. Previous studies showed that users of virtual reality systems can experience cybersickness during virtual environment exposure and this may last for several hours after exposure (Stanney & Kennedy, 1998). The common symptoms of cybersickness are nausea, eyestrain and postural instability.

2.1.2. Measurements using questionnaires

To study cybersickness, it is important to quantify the levels of cybersickness experienced by the users of virtual reality systems. There are several methods being used by different researchers. One of these is to assess the severity of this feeling by using questionnaires, i.e. ask the users of virtual reality systems to rate their feeling according to different scales.

2.1.2.1. Nausea Rating

Nausea is a common symptom of different types of motion sickness such as carsickness and seasickness. It is also a usual and representative symptom associated with cybersickness. Golding & Kerguelen (1992) proposed a 7-point nausea rating in assessing the motion sickness experienced by their experiment participants (Appendix A). This scale has been adopted in various motion sickness related research (Lo, 1998; So et al., 2001; So et al., 2001a; Woodman & Griffin, 1997).

2.1.2.2. Simulator Sickness Questionnaire

Simulator Sickness Questionnaire was developed by Kennedy and his colleagues in 1993 (Kennedy et al., 1993). They used over 1000 sets of previous data and through some analysis, they came up with a list of 27 symptoms which are commonly experienced by users of virtual reality systems. Each item is rated with the scale from none, slight, moderate to severe. Through some calculations, four representative scores can be found (Appendix B). Nausea-related subscore (N), Oculomotor-related subscore (O), Disorientation-related subscore (D) are the scores for the symptoms for the specific aspects. Total Score (TS) is the score representing the overall severity of cybersickness experienced by the users of virtual reality systems. Simulator Sickness Questionnaire is a widely applied measurement tool in research studying simulator sickness and cybersickness.

2.1.2.3. Advantages and Disadvantages

Using questionnaires and different scales is an easy and direct way of assessing the severity of cybersickness experienced by the users of virtual reality systems. However, all the data is the subjective feelings of users and it is probable that different individuals would have different personal scales. Therefore, even though they may have similar levels of cybersickness, they may give different results according to the same scales.

2.1.3. Measurements using postural tests

To overcome the problem of subjective measurements using questionnaires, many studies use postural tests to assess the severity of sickness of users of virtual reality systems. Postural instability is another common symptoms found among users of virtual reality systems and this could be used as an index for the severity of cybersickness experienced by them. Postural tests can be categorized into two groups: dynamic postural tests and static postural tests.

2.1.3.1. Dynamic Test

Several dynamic postural tests were designed in order to check the users' ability to balance their bodies when walking. For different postural tests, different indicators were used as a reference for the severity of cybersickness experienced by the users of virtual reality systems.

2.1.3.1.1. Walk on floor eyes closed (WOFEC)

This test requires the participants to walk heel-to-toe, with arms folded across chest and eyes closed for 10 or 12 steps without sidestepping. To walk heel-to-toe means that the heel of one foot has to touch the toe of the other foot for each step (Figure 2.1). The indicator of postural stability in this test is the number of steps that the participants can make without sidestepping or falling down (Cobb, 1999; Kennedy et al, 1993; Thomley et al., 1986).

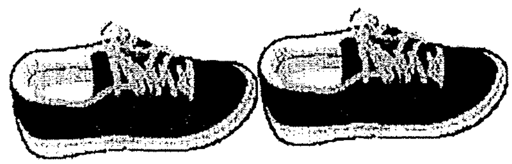


Figure 2.1
Illustration of heel-to-toe posture

2.1.3.1.2. Walk on rail eyes open (WOREO)

This test is similar to the Walk on floor eyes closed test except that participants have to walk on a narrow rail rather than walking on the floor. Moreover, they are allowed to open their eyes. The indicator used is the same as WOFEC, that is, the number of steps that the participants can make without sidestepping or falling down (Hamilton et al., 1989).

2.1.3.1.3. Walk on line eyes closed (WOLEC)

This test is also similar to Walk on floor eyes closed test. However, the indicator used is different. Participants have to walk for a distance of 4 meters with heel-to-toe steps, arms folded across chest and eyes closed. Sidestepping is allowed in this test. The indicator used is the deviation from the expected end point in a straight line and the actual position they reached after the walk (Cobb, 1999; Hamilton et al., 1989).

2.1.3.1.4. Walk heel-to-toe around a 4m-long set path (WASP)

This test is designed by Cobb (1999) and it required the participants to walk heel-to-toe along a 4m-long set path with eyes open. The path consists of three turns, a 180° curvature, 35° inclination, 14cm high steps and obstacle (Figure 2.2). The participants are asked to complete the path as fast as possible and they are required to bend down to remove the obstacle halfway along the path. The indicator for the test is the performance time, that is, the time needed to complete the path.

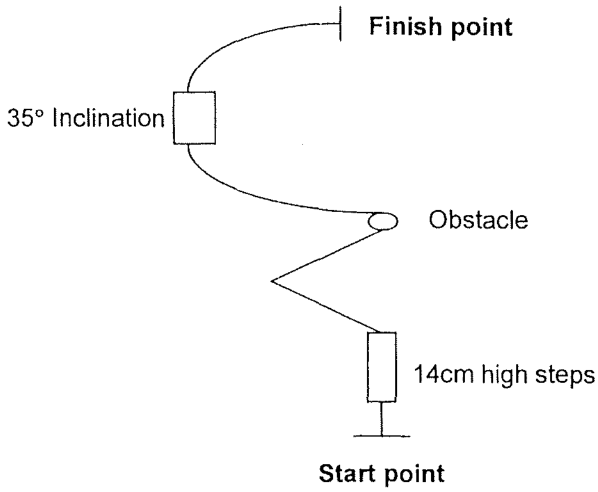


Figure 2.2 The path (4 meters long) for the WASP test (adopted from Cobb, 1999)

2.1.3.2. Static Test

Static postural tests require the participants to keep a specific posture and try their best to balance themselves for a period of time. Kennedy and Stanney (1996) listed the possible combinations of static postural tests (Appendix C).

The indicators used for static postural tests are more standardized than the dynamic ones. Several measurements are being commonly used as indicators of postural stability in different research for the static postural tests. The most common one is the length of time that the participants can balance themselves (Cobb, 1999; Cobb & Nichols, 1998; Hamilton et al., 1989; Kennedy et al., 1993; Kennedy & Stanney, 1996; Kennedy et al., 1997; Thomley et al., 1986, Yoo et al, 1997; Yoo & Lee, 1999).

Besides balancing time, Kennedy & Stanney (1996) proposed the measurement of head deviation using a high contrast reticle to measure the velocity of head movement. The postural test would be video taped and the size of the reticle would be record frame by frame in the video. The velocity of head movement in different directions could then be calculated.

Other measurements were also used in different research. Cobb and Nichols measured the hip sway of participants during the postural tests using the SWAY Magnetometry System (Cobb, 1999; Cobb & Nichols, 1998) while Murata and Miyoshi (2000) used the force platform to measure the movement of the center of gravity of the participants.

2.1.3.2.1. Normal Stance

This is the normal way of standing. Participants need to stand still, with their arms by sides and eyes closed. As this is the most natural way of standing, past studies show that even after virtual environment exposure, most of the participants could still keep this posture for the required time. Hence, the effect of cybersickness is difficult to be observed by using time as an indicator. Cobb, on the contrary, found that the hip sway during the normal stance is sensitive but the effect is mild (Cobb, 1999).

2.1.3.2.2. Sharpened Romberg (SR)

Sharpened Romberg (Figure 2.3) test, also known as Tandem Romberg test, is a common static postural test. It requires participants to stand heel-to-toe, with eyes closed and arms folded across chest. The usual duration for this test is 60 seconds (Cobb, 1999; Cobb & Nichols, 1998; Hamilton et al., 1989; Kennedy et al., 1993; Kennedy & Stanney, 1996; Thomley et al., 1986, Yoo et al, 1997).

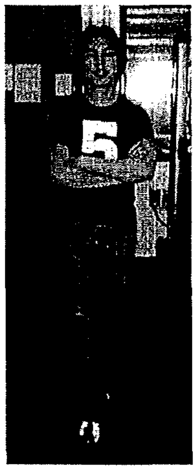


Figure 2.3 Illustration of Sharpened Romberg posture

2.1.3.2.3. Stand on One Leg Eyes Closed (SOLEC)

Stand on One Leg Eyes Closed test (Figure 2.4) could be further divided into Stand On Preferred Leg (SOPL) and Stand On Non-preferred Leg (SONL) tests. As defined by the name of the test, participants are required to stand with the preferred or

Figure 2.4 Illustration of Stand On One Leg Eye Closed posture

non-preferred leg. They have to fold their arms across chest with eyes closed. The usual duration for this test is 30 seconds (Hamilton et al., 1989; Kennedy et al., 1993; Kennedy & Stanney, 1996; Kennedy et al., 1997; Murata & Miyoshi, 2000; Thomley et al., 1986). The determination of the preferred leg and non-preferred leg varies from different research. Kennedy & Stanney (1996) asked their participants to stand on one leg with no further instruction and considered their choice as their preferred legs.

2.1.3.3. Advantages and Disadvantages

One of the advantages of the postural tests is all the data are from objective measurement. However, it was discovered that participants can learn the skills of balancing themselves from trial to trial. That is, there may be a learning effect affecting the results. To deal with the learning effect, some studies used trained subjects to participate in their experiment (Hamilton et al., 1989). They ask the participants to practice the postural tests for a period of time until they are familiar with them before participating in the virtual reality experiments. Others screen out the participants by only selecting those who can keep their posture with maximum time before the virtual reality exposure (Stoffregen et al., 2000).

Previous studies also found that the reliability of the dynamic postural tests is less than that in static postural tests. Their results showed that the Stand On Non-preferred Leg test is of the highest reliability (Hamilton et al., 1989; Thomley et al., 1986).

2.2. Possible causes of cybersickness

2.2.1. Sensory rearrangement theory: cybersickness as a type of visually induced motion sickness

According to the Sensory rearrangement theory from Reason and Brand (1978), a possible cause of motion sickness is that there is a mismatch in stimuli given to different human systems. Specifically for cybersickness, when using the virtual reality systems, the visual systems of the users of virtual reality systems perceive motion from the visual scene. On the contrary, their vestibular systems perceive the body as stationary since they are usually sitting down or standing still during the virtual reality exposure. Therefore, there are noticeable visual stimuli given to the users while having no or little vestibular stimuli. This mismatch could be a possible cause for the raising of cybersickness.

2.2.2. Visual stimuli as a major cause of cybersickness

As there are noticeable stimuli given to the visual system of the users of virtual reality systems, it is reasonable to believe that the visual stimuli are a major cause of cybersickness. Imagine that if the users of virtual reality systems block the visual stimuli by closing their eyes during the virtual reality exposure, it is probable that they would not experience any cybersickness.

A common phenomenon occurring with cybersickness is the presence of vection. Vection is the illusion of self-motion. Hettinger et al. (1990) showed that vection is a precondition for cybersickness.

2.2.2.1. The two components of visual stimuli: scene velocity and scene complexity

There are two main components relevant to the visual stimuli during the virtual reality exposure. They are the scene velocity (the velocity of navigation in the virtual environment) and the scene complexity (the complexity of the scene content in the virtual environment). So et al. (2001a) studied the effect of 7 different navigation speed in a virtual environment on the levels of cybersickness. Their results showed that levels of cybersickness, reflected by nausea ratings, increase when navigation speed increase from 3 m/s to 10 m/s. Beyond 10 m/s up to 59 m/s, the nausea ratings stabilized.

Chapter 3. Literature Review on How to Measure scene complexity of a virtual environment

3.1. Scene Complexity: Definition

To define scene complexity, we can consider the visual scene in a television, which is the same as that in a virtual environment shown on the head-mounted display. A typical TV signal consists of various portions. The ones responsible for the video signal are the luminance or visual carrier and the chrominance or chroma carrier (Ovadia, 2001). Luminance is the brightness portion, containing all the information of the picture details while chrominance is the color portion, containing information about the picture hue (or tint) and color saturation. Based on the above, it is reasonable to define scene complexity in virtual environments to have two basic components: the luminance component and the chrominance component.

3.2. Measurement of scene complexity and the influence of the 'two visual systems' theory

To measure the scene complexity in a virtual environment, we need to determine both the chrominance component and the luminance component. However, the calculation may become too complex if the effects of both components are to be included in the measurement. Hence, it is suggested that only the more important component is used to represent the scene complexity in the virtual environment.

Many studies propose that the detection of motion and color is from different areas of the brain. The study from Livingstone and Hubel (1988) suggests two different channels, the parvocellular and magnocellular channels. The parvo units are responsible for color and detailed information while the magno units play a role in detecting motion and are responsible for rough information.

The two visual systems theory was proposed by Schneider (1967, 1967a) (Appendix D). They suggested that human visual system consists of the focal vision and the ambient vision. The focal vision is responsible for detailed information such as object identification and discrimination while the ambient vision is for spatial localization and orientation. Hence motion detection probably deals with the ambient vision which involves coarse details only.

Based on the above, it is probable that color is not important during motion perception. Therefore, color should have no significant effect on the levels of vection or cybersickness. In quantifying the scene complexity in the virtual environment, between the chrominance and luminance factors, luminance seems to have a more important effect than the chrominance factor. As the method of quantification for the scene complexity is still in a very early stage, for the ease of study, chrominance factor is neglected in this stage.

3.3. The use of spatial frequency in quantifying the luminance component of scene complexity

3.3.1. Definition of spatial frequency and its use in studies of rotating drums

Spatial frequency is a measurement of frequency of spatial variations in luminance level (So, et al., 2001). It has been commonly used in quantifying the scene complexity of the visual field in most of the studies on motion sickness induced by rotating drum. This is already a widely adopted standard for the rotating drum studies. The unit for spatial frequency is cycle per degree (cpd).

3.3.2. Previously reported algorithms in calculating the average spatial frequency of a captured picture inside a virtual environment

Measurement of scene complexity is also a very important aspect in studying its effect on cybersickness. There is no standard for the quantification of scene complexity in the virtual environment. Barfield et al. (1990) defined scene complexity as the frequency of occurrence of objects or surfaces in the virtual environment. However, with the increasing realism in virtual environment, this method may not be able to represent the scene complexity precisely. Kennedy et al. (1996) proposed the Human Judged Kinematics Cluster Scores which used trained research assistants to measure the visual stimuli in the virtual environment based on certain rules. Nevertheless, it requires a labor-intensive process and the measurement is subjective.

So et al. (2001) extended that idea to quantify the scene complexity of a virtual reality simulation (Appendix E). The captured color pictures were first converted to a gray scale, Portable Gray Map (pgm) format. Most of the graphical software such as ImageMagick™ from ImageMagick Studio has this conversion function. It uses the Red Green Blue (RGB) components of each pixel to find out the corresponding grayscale (Hoffmann, 2002).

Red, Green, Blue (RGB) to Grayscale
Grayscale = 0.3R + 0.59G + 0.11B

R = 168
G = 60 $\longrightarrow$
B = 165

Grayscale
= 0.3(168) + 0.59(60) + 0.11(165)
= 104

Figure 3.1 Algorithm for converting color to grayscale

For each horizontal and vertical line of the picture, the Power Spectral Density Distribution is extracted. The average spatial frequencies in the horizontal, vertical and radial axes of the sampled snapshots could then be calculated and be used as the reference of the scene complexity of the virtual environment. As the main axis of movement in the virtual simulation is the fore-and-aft axis, the radial dimension of the visual scene would be affected. It is used as the main reference in this thesis. In calculating the representative spatial frequency for the snapshots, three algorithms have been suggested to calculate (So et al, 2001).

3.3.2.1. Mean

Mean method calculates the average spatial frequency according to the Power Spectral Density (PSD) distribution to represent the frequency of the line.

3.3.2.2. Mode

Mode method uses the spatial frequency at which the amount of luminance variations peaked as the representative frequency for the specific line.

3.3.2.3. Combined

The combined method calculates the dominant spatial frequency according to the following equation:

Dominant spatial frequency = Average of (frequency at which the spatial frequency PSD has the highest peak + all other frequencies at which the values of spatial frequency PSD is greater than half of the maximum peak).

3.3.3. The choice of algorithm for quantifying spatial frequency

According the two visual systems, the fine details, the high spatial frequency stimuli, should have no significant effect on the levels of vection. Thus it is suspected that it also has no significant effect on the levels of cybersickness. Blurring, which would eliminate the high frequency of the pictures, should have little effect on the scene complexity in order to ensure similar levels of cybersickness. However, the results in So et al. (2001) showed that there is a significant drop in spatial frequency when adopting the mean algorithm. Hence, the mean algorithm may not be a good one for finding the representative spatial frequency of the virtual environment. The mode algorithm, on the other hand, may eliminate the effect of other frequencies which also have high amplitudes. Therefore, in this research, the combined algorithm is used in calculating the radial spatial frequency of the virtual environments.

3.3.4. The calculation of the average radial spatial frequency of a virtual environment

To represent the scene complexity in a virtual environment, a number of snapshots are captured. As there is no algorithm for the optimal number of snapshots to be captured, a previous study from So et al. (2001) sampled 2 pictures per second in the virtual environment during a 30-minute simulation. Over 3000 snapshots are captured to ensure the calculated value is a reliable and representative one for the scene complexity of the virtual environment.

3.4. Measurement of color

Although the chrominance factor is considered to be less important in the scene complexity, the effects of it on cybersickness are still unknown. The measurement of color becomes another issue to be determined. The color signal in the television can be divided into red, green and blue components, known as RGB signal. This RGB code is used in most of the computer graphics editors too. For each component, it can range from 0 to 255. Sample color is shown is Figure 3.2. With this 255 × 255 × 255 combinations, over 16 millions of colors can be generated. This RGB code could be a representative measurement for different colors.

Figure 3.2 Illustration of colors represented by RGB code

3.5. Past studies concerning effects of color and spatial frequency on cybersickness

There are not many studies investigating the effects of scene complexity on levels of cybersickness. So et al. (2001) used virtual environments of three different scene complexities and preliminary results showed that the higher the scene complexity, the greater the levels of cybersickness. Hence, there is a need for further study on the effects of scene complexity in virtual environment.

3.5.1. Previous studies of spatial frequency on visually-induced motion sickness other than cybersickness

Although there are not many studies investigating the effects of visual stimuli on the levels of cybersickness, there are a number of them investigating the effects of visual stimuli on motion sickness. The common visual stimuli are the rotating drum and the optical flow.

3.5.1.1. Previous studies on rotating drum experiments

One common type of study investigating the effects of visual stimuli is the rotating drum experiments. Rotating drum, also known as vection drum, is a drum with alternative black and white stripes. The more pairs of alternative black and white stripes, the higher the visual stimuli given to the participants. The change from black to white stripes, which is characterized by the change in luminance level, is usually quantified in terms of spatial frequency with unit as cycle per degree (cpd).

Hu et al. (1997) studied the effect of rotating drum with different spatial frequencies on levels of motion sickness. The spatial frequencies range from 0.0167cpd to 0.267cpd. The drum rotating speed is 60 degree/second, or 10 revolutions per minute (rpm). Their results showed that sickness of the participants increase as spatial frequency increase, and is peaked when spatial frequency reach 0.067cpd. Beyond 0.067cpd, the levels of sickness decrease again.

3.5.1.2. Previous studies on effects of optical flow on levels of vection and sickness in simulators

Optical flow is the flow patterns of visual objects perceived by a participant during a flight simulation session. Its relationship with the levels of vection and simulator sickness has been topics of many researchers. Previous studies showed that higher optical flow would lead to greater sickness among participants (Sharkey & McCauley, 1991).

3.5.2. Previous studies on effects of scene color and patterns

Another important factor in the visual stimulus is the color and patterns or texture of the scene. Much research has been done on investigating the effect of color and patterns on the levels of vection. Most of them agree that color and motion are detected by different part of the visual systems. Hence, the part that used for detecting motion is not sensitive to color and color is not important for the detection of motion (Livingstone & Hubel, 1988). As vection is a precondition for cybersickness, it is suspected that color also has no significant effect on the levels of cybersickness.

Previc et al. studied the effect of visual scene effects and they concluded that better texture and color would not make the VR system users feel more realistic (Previc et al, 1992). Kolasinski (1995) also suggested that color would not have significant effect of the levels of cybersickness. Muller et al. (1990), on the other hand, studied the effect of different pattern on the levels of vection and their results showed patterns have no significant effect on levels of vection.

Chapter 4. Optimization in the calculation of average spatial frequency of a virtual environment

4.1. Algorithm for determining the optimal number of scenes in the Virtual Environment to be sampled

Currently, there is no algorithm for determining the optimal numbers of snapshots to be captured in the virtual environment. In the experiment fromSo et al. (2001), sampling at 2 snapshots per second is used. However, capturing snapshots is quite labor-intensive and it may not be necessary if we could develop a method to find out the optimal number of snapshots we need to capture in order to accurately represent the whole virtual environment.

4.1.1. Preliminary test on the number of snapshots to be captured

To search for an optimal number of snapshots to be captured, a preliminary test wascarried out todetermine the change of mean and variance in radial spatial frequency with increase in number of snapshots. 2 pictures, 4 pictures, 8 pictures, 16 pictures and 32 pictures were captured randomly 8 times. Their average radial spatial frequencies are shown is Figure 4.1.

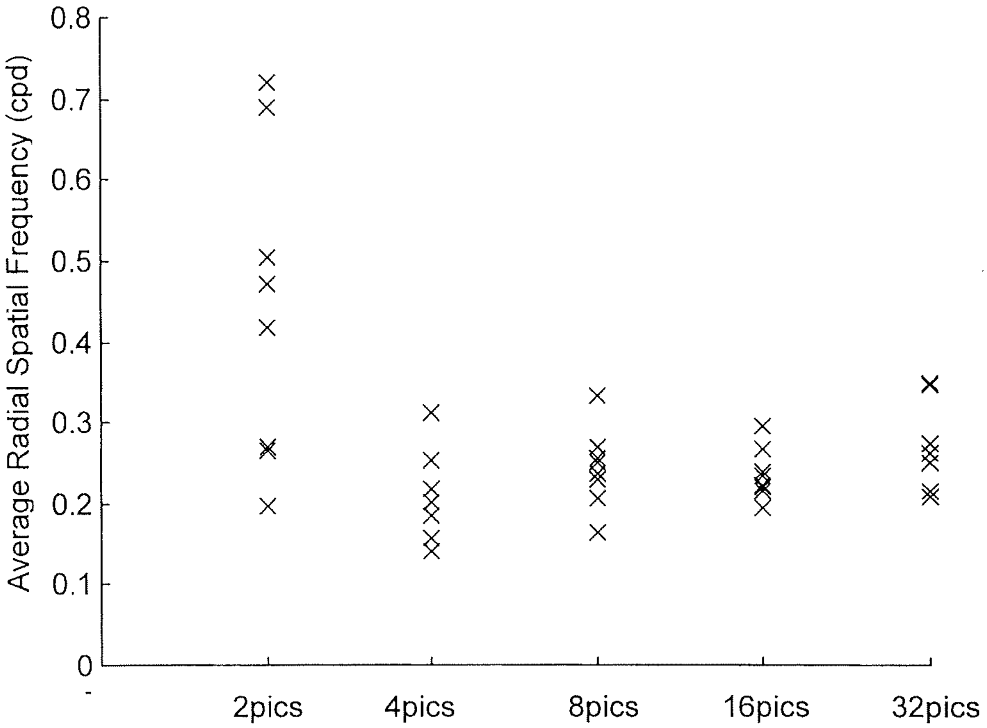


Figure 4.1 The average radial spatial frequency of the preliminary test.

Statistical tests showed that the average radial spatial frequencies are significant different fordifferent numbers of pictures captured. Student-Newman-Keuls (SNK) Test showed that the 2-picture case is significant different from the other cases (Table 4.1).

Table 4.1 Statistical test results of the preliminary study

Dependent Variable: Radial Spatial Frequency

Source	df	Sum of Squares	Mean Square	F Value	Pr > F
Random No.	4	0.26120300	0.06530075	5.66	0.0013
Error	35	0.40396936	0.01154198		
Corrected Total	39	0.66517236			

SNK Grouping		Mean	N	CONDS
A		0.40368	8	2pics
	B	0.17920	8	4pics
	B	0.21155	8	8pics
	B	0.19995	8	16pics
	B	0.24116	8	32pics

4.1.2. Random Sampling

According to the Central Limit Theorem (Miller, 1983; Schefler, 1988), if the number of samples were large enough, their distribution would follow the normal distribution.

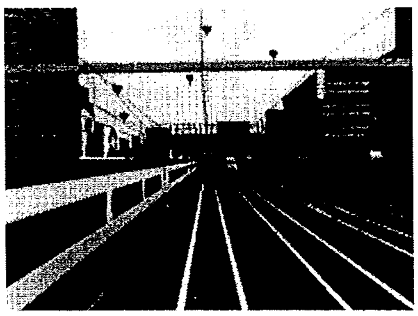


Figure 4.2 Metropolitan city virtual environment used in previous experiment (So et al, 2001)

For the virtual environment used in the preliminary study (Figure 4.2), the computer can update the virtual environment with 30 frames per second. Hence, for a 30-minute simulation, there will be in total 30 frames/sec × 30 min × 60 sec = 54000 frames presented during the virtual environment snapshots. As the number of samples is large, we may assume that it follows the normal distribution.

Since the distribution of spatial frequencies is normally distributed, simple random sampling can be used for determining the number of pictures to be captured in a virtual environment. We have the statistical formula as follow (Thompson, 1992; Thompson & Seber, 1996):

$$
\begin{aligned}
& P\left(\left|\overline{X}-\mu\right| \le \varepsilon\right) \ge 1-\alpha \\
& \Rightarrow P\left(\frac{\sqrt{n}\left|\overline{X}-\mu\right|}{\sigma} \le \frac{\sqrt{n}\varepsilon}{\sigma}\right) \ge 1-\alpha \\
& \approx P\left(Z \le \frac{\sqrt{n}\varepsilon}{\sigma}\right) \ge 1-\alpha \\
& \Rightarrow \frac{\sqrt{n}\varepsilon}{\sigma} \ge z_{\frac{\alpha}{2}} \\
& \Rightarrow n \ge \frac{z_{\frac{\alpha}{2}}^{2}\sigma^{2}}{\varepsilon^{2}} \approx \frac{z_{\frac{\alpha}{2}}^{2}s^{2}}{\varepsilon^{2}}
\end{aligned}
$$

where α = probability of rejecting the statistical hypothesis tested

σ = standard deviation of the sample

ε = error between the sample mean and the true population mean

Hence, to determine *n* which is the required sample size, we have to set the error and the probability of rejecting the test. An initial sample is also needed to determine the sample variance. As shown in the preliminary study, there is no significant difference between the 2-picture and 4-picture cases. It is probable that the optimal size would be between 2 $\times$8 =16 and 4 $\times$ 8 = 32 pictures. Hence, we set the initial sample size equals 16 snapshots. With this, we can find out the sample deviation, σ. Also, we could set the error, ε, at a level equals to around 10% of the initial sample mean. For α, as a usual practice, we would set it at a 5% level.

4.1.3. Verifications

To verify the method, we captured 16 snapshots from the virtual environment used in So et al. (2001). The basic statistics are as follow:

Statistical results of the first 16 samples	
Mean	0.261cpd
Standard Deviation, σ	0.077cpd

Setting α = 5%, ε = 0.02cpd (around 10% of the mean of the initial samples), we have the corresponding n = 29. Therefore, 13 more snapshots were captured and the corresponding mean and standard deviation of the 29 snapshots are 0.319cpd and 0.135cpd respectively.

Comparing the above data with those from So et al. (2001) which samples at 2 pictures per second (i.e. 3600 samples), having the mean radial spatial frequency equals 0.332cpd with standard deviation equals 0.152cpd. Statistical tests showed that there is no significant difference between average radial spatial frequency of the 29 samples and the 3600 samples ($p>0.45$) (Table 4.2).

Table 4.2 Statistical test comparing the average radial spatial frequency between the optimal number of sample and the over-sampled data.

ANOVA test

Dependent Variable: Metropolitan VE

Source	Sum of Squares	df	Mean Square	F	Sig.
Level	1.297E-02	1	1.297E-02	.561	.454
Error	92.367	3995	2.312E-02		
Corrected Total	92.380	3996			

Apart from using the data from So el al. (2001), sampled snapshots from the virtual environment used in this research are also captured in order to verify the above algorithm (Figure 4.3).

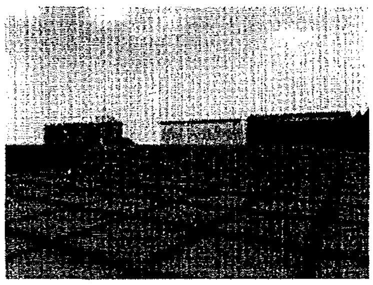


Figure 4.3 Virtual environment used in this research (sea-front scene)

The statistical results for the initial 16 snapshots are as follow:

Statistical results of the first 16 samples	
Mean	0.113cpd
Standard Deviation, σ	0.053cpd

Setting $\alpha = 5\%$, $\varepsilon = 0.01$cpd (around 10% of the mean of the initial samples), we have the corresponding n = 57. Therefore, 41 more snapshots were captured and the corresponding mean and standard deviation of the 57 snapshots are 0.129cpd and 0.054cpd respectively.

Comparing the above data with data from sampling at 2 snapshots per second (i.e. 3600 samples), having the mean radial spatial frequency equals 0.132cpd with standard deviation equals 0.065cpd. Statistical tests showed that there is no significant difference between average radial spatial frequency of the 57 samples and 3600 samples ($p>0.68$) (Table 4.3).

Table 4.3 Statistical test comparing the average radial spatial frequency between the optimal number of sample and the over-sampled data.

ANOVA test

Dependent Variable: Sea-front VE

Source	Sum of Squares	df	Mean Square	F	Sig.
Level	6.953E-04	1	6.953E-04	.166	.684
Error	15.338	3655	4.196E-03		
Corrected Total	15.338	3656			

Therefore, in the two virtual environments, the proposed sampling algorithm can determine the optimal number of snapshots to be captured. Statistical test results showed that the calculated spatial frequency from the optimal number of snapshots could accurately represent the spatial frequency of the virtual environments.

4.2. Considering the effects of display degradation

One of the important parameter in describing a computer graphic is its resolution. With same picture size, a picture with higher resolution would have a more detail and clear figure (Figure 4.4). However, due to certain restrictions such as hardware limitations, highest resolution may not be used all the time. A high-resolution picture may then be degraded to a lower one to match different situation.

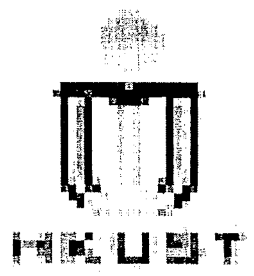
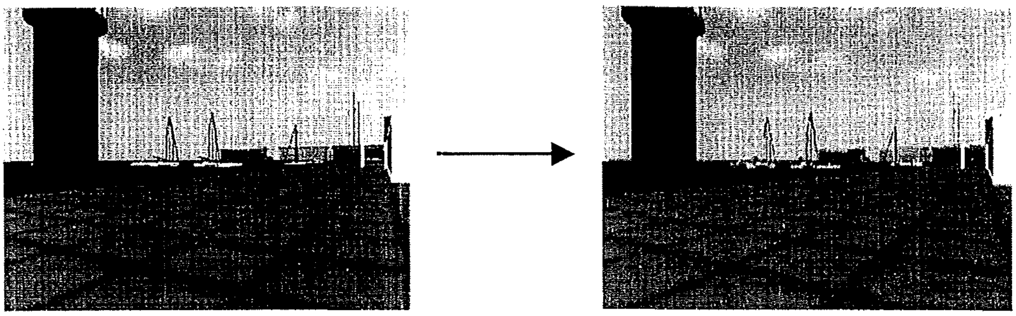
		
384 pixels × 384 pixels	77 pixels × 77pixels	38 pixels × 38 pixels

Figure 4.4 Illustration of effect of degradation on a sample picture

In the experiment in So et al. (2001), snapshots were captured with resolution of 640 pixels × 480 pixels. However, the VR4 head-mounted display used to present the virtual environment to the experiment participants only has resolution of 495 pixels × 115 pixels only. This raises a need to degrade the sample snapshots before calculating the spatial frequency of them in order to better represent the visual stimuli seen by the users of virtual reality systems. In this research, as the VR4 head-mounted display was used, all the captured snapshots was degraded to a resolution of 495 pixels × 115 pixels before the spatial frequency was calculated.

Figure 4.5 gives an illustration of the effect of degradation of a sample snapshot. After degradation, although the snapshot becomes less detail, the main figure is still clear and the radial spatial frequency of the snapshot is reduced from 0.1963cpd to 0.1164cpd.



Radial Spatial Frequency

Original 0.1963cpd

Degraded 0.1164cpd

Figure 4.5 Illustration of effect of degradation on a snapshot of a sea-front virtual environment

To verify the significance of this reduction, the average radial spatial frequency of the 57 pictures captured from the sea-front VE were calculated with and without applying the degradation. Statistical test showed that the radial spatial frequency was significantly decreased after the degradation (Table 4.4).

Table 4.4 Statistical test for the effect of degradation on radial spatial frequency

	Without degradation (640 pixels × 480 pixels)	With degradation (495 pixels × 115 pixels)
Mean	0.239cpd	0.129cpd
Standard Deviation	0.056cpd	0.054cpd

Dependent Variable: Radial Spatial Frequency

Source	Sum of Squares	df	Mean Square	F	Sig.
LEVEL	.344	1	.344	113.633	.000
Error	.339	112	3.023E-03		
Corrected Total	.682	113			

Chapter 5. Cybersickness in similar virtual environments with different color (Experiment 1) – Partial verification of the two visual systems theory

5.1. Objectives & hypotheses

The two visual systems theory suggested that motion is detected by the ambient vision which is insensitive to color. Based on this, when we compute the spatial frequency of virtual environments, we neglect the chrominance factor and use the gray scale of snapshots for the calculation. Experiment by So et al. (2001) was making the assumption that the two visual systems theory is true. However, there are still no experimental results supporting the use of this theory. Therefore, an experiment was conducted to study the effects of color on the levels of cybersickness.

The design of the experiment is a mixed one. The color of virtual environments and gender are between-subject design while the duration of exposure is a with-in subject design.

As it is assumed that the two visual systems theory is true, it is hypothesized that there is no significant effects of color on the levels of cybersickness. It is also hypothesized that nausea rating would increase significantly with longer exposure time.

In addition to the above, the effects of gender are also studied in this experiment. For the effects of gender, previous studies are quite disagreeing among themselves. Some found that male are higher sickness levels than female while others found the opposite results (Yoo et al., 1997). However, most of them found that the effect of gender is not significant. Hence we hypothesized that there is no significant difference between the two genders on the levels of cybersickness.

Four similar sea-front virtual environments with different color combinations of sea and ground were built (Figure 5.2). They were developed so that their grayscales look more or less the same (Figure 5.3). An illustration of color having similar grayscale is presented in Figure 5.4. This illustration shows the possibility of make environments of different colors but with similar grayscale. To generate different color with similar grayscale, graphic editing software, Paint Shop Pro® version 6 from Jasc Software®, Eden Prairie, USA, is used. In this experiment, two main parts in the virtual environment, i.e. the sea and the ground, were mapped with different colors. The sea is either green or blue and the ground is either gray or brown. Hence, we have 4 different combinations of colors for sea and ground forming the 4 virtual environments. The generation of the colors is to add different percentage of RGB components to a grayscale picture (Figure 5.1).

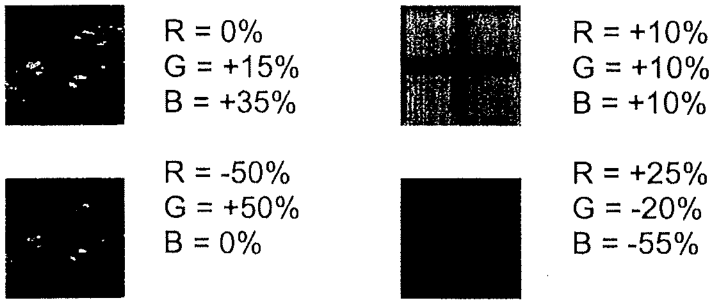
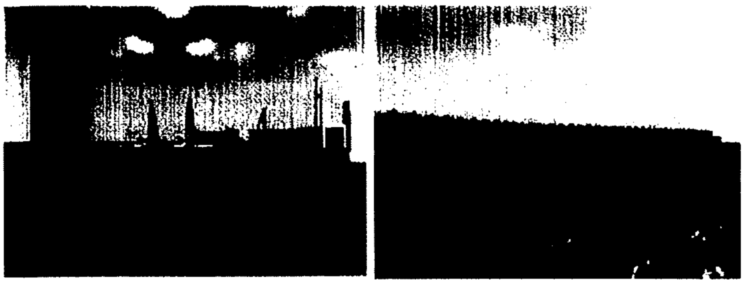


Figure 5.1 The RGB coding for the sea and ground in different virtual environments

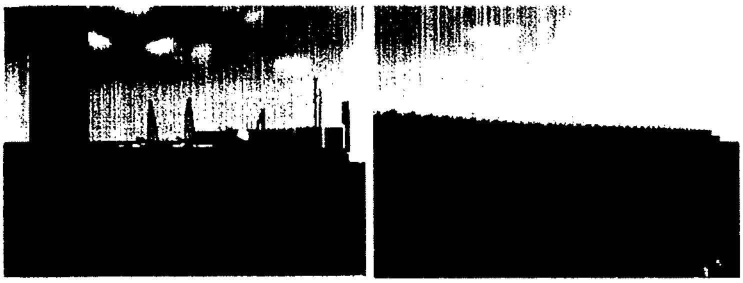
The colors in the virtual environment are chosen as natural as possible in order to eliminate unwanted effect. E.g. the sea could be blue or green but not yellow. The average radial spatial frequency of the virtual environments ranges from 0.108cpd to 0.114cpd and they were found statistical the same ($p>0.9$) (Table 5.1).

Virtual environment with blue sea and gray floor



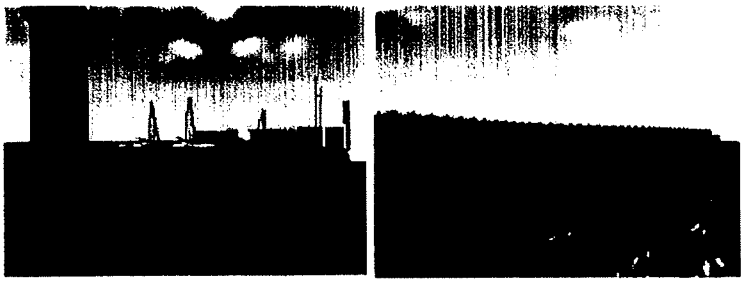
Average Radial
Spatial Frequency
= 0.129cpd

Virtual environment with green sea and gray floor



Average Radial
Spatial Frequency
= 0.127cpd

Virtual environment with blue sea and brown floor



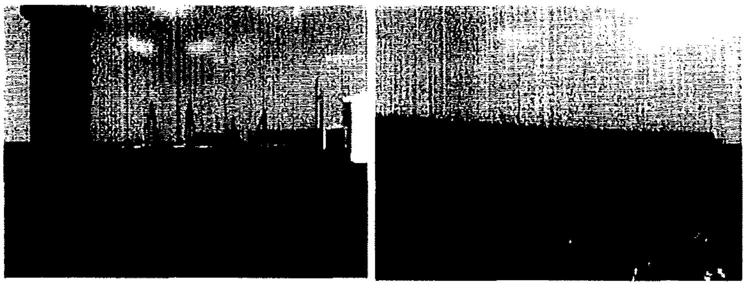
Average Radial
Spatial Frequency
= 0.129cpd

Virtual environment with green sea and brown floor

Average Radial
Spatial Frequency
= 0.124cpd

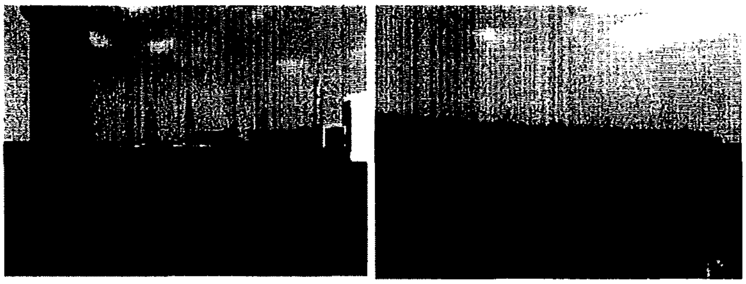
Figure 5.2 Snapshots of the 4 sea-front virtual environments with different color combinations from the same view angle and their corresponding average radial spatial frequencies. (in color)

Virtual environment with blue sea and gray floor



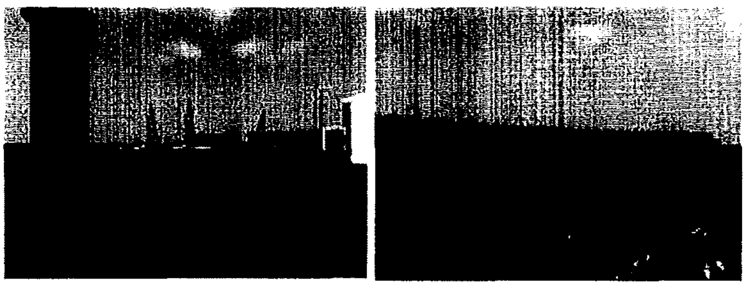
Average Radial Spatial Frequency = 0.129cpd

Virtual environment with green sea and gray floor



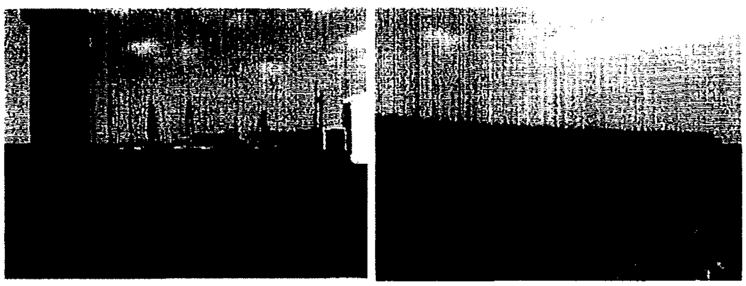
Average Radial Spatial Frequency = 0.127cpd

Virtual environment with blue sea and brown floor



Average Radial Spatial Frequency = 0.129cpd

Virtual environment with green sea and brown floor



Average Radial Spatial Frequency = 0.124cpd

Figure 5.3 Snapshots of the 4 sea-front virtual environments with different color combinations from the same view angle and their corresponding average radial spatial frequencies. (in grayscale)

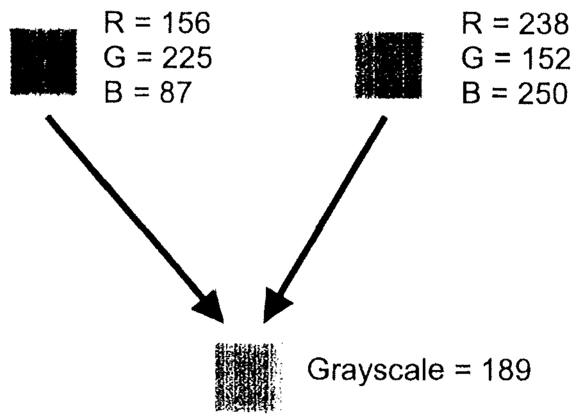


Figure 5.4 Illustration of different color having same grayscale

Table 5.1 Statistical test on the radial spatial frequency of the 4 virtual environments with different colors

ANOVA test

Source	Sum of Squares	df	Mean Square	F	Sig.
LEVEL	9.910E-04	3	3.303E-04	.124	.946
Error	.598	224	2.670E-03		
Corrected Total	.599	227			

5.2. Procedures

Sixty-four Chinese aged between 19 and 27 participated in the experiment. They were randomly assigned to one of the virtual environments with equal number of each gender. They were all healthy with normal eyesight. Color blindness test is conducted before the experiment to ensure they do not have color blindness. They were paid $50/hr for their time.

Upon arrival to the experiment, all participants were asked to fill in the pre-exposure Simulator Sickness Questionnaire. Several static postural tests would be conducted afterwards. Participants had to carry out four trials of

Sharpened Romberg tests followed by three trials of both Stand On Preferred Leg and Stand On Non-preferred Leg tests with alternating order. The measurements taken for the postural tests are the time that they can balance themselves and the deviation of their heads during the tests. They would then assign randomly to one of the virtual environments. The exposure time is 40 minutes.

In the virtual environment, the viewpoint was moved according to a pre-determined path. The main axis of movement is the fore-and-aft axis, i.e. the main movement is moving forward. To increase the interaction with the virtual environment and to make the participants more involved in it, the participants were asked to turn their heads for every 30 second. These movements are suggested to have no effect on levels of cybersickness as the viewpoint was moving according to the movement of the head. Therefore, there is no conflict between the stimuli given to the vestibular and visual systems. Hence, from the sensory re-arrangement theory, it would not cause any sickness.

During the 40-minute virtual environment exposure, participants would be asked for their sickness based on the 7-point nausea rating (Golding & Kerguelen, 1992) and their feeling of being moving based on the 4-point vection rating (Appendix F) (Hettinger et al., 1990) in every 5 minutes intervals. On exit to the virtual environment, a post-exposure Simulator Sickness Questionnaire would be given to the participants and all the static postural tests would be conducted again.

5.3. Apparatus

A Virtual Research VR4 LCD Head-Mounted Display (HMD) with a field-of-view of 48º (36º was used to present the virtual environments. All the virtual environments were rendered with the dVISE software in Silicon Graphic ONXY II InfiniteReality Workstation with frame rate of 30 frames per second. Polhemus 3-Space magnetic tracker was used to measure the head position and orientation during the virtual reality simulation. Another Polhemus 3-Space magnetic tracker was fixed on the heads of the participants using a earmuff and it was used, with the program developed with the WorldToolKit® software, to keep track with the head movement of the participants throughout the postural tests.

5.4. Results

5.4.1. Nausea Rating and Vection Rating

Table 5.2 and 5.3 showed the ANOVA test results of the effects of different factors on nausea rating and vection ratings. For both ratings, it is found that the exposure time is having significantly effect ($p<0.05$). Figure 5.5 and 5.6 show the graph of nausea rating and vection rating versus duration of exposure. They both showed an increasing trend. Student-Newman-Keuls test in Table 5.4 nausea rating increase significantly from 0 minute to 25 minutes. From 25 minute to 40 minute virtual environment exposure, nausea rating did not significantly increase. For vection rating, it increased significantly from 0 minute to 10 minutes. From 10 minutes to 40 minutes, it did not significantly increase.

For the effect of color and gender, both show no significant effect on nausea rating and vection rating ($p>0.1$). These agree with our hypothesis.

Table 5.2 ANOVA tests on Nausea Rating

Source	Sum of Squares	df	Mean Square	F	Sig.
TIME	169.094	8	21.137	22.409	.000
GENDER	1.266	1	1.266	1.342	.247
COLOR	3.352	3	1.117	1.185	.315
TIME * COLOR	2.601	24	.108	.115	1.000
TIME * GENDER	3.469	8	.434	.460	.884
COLOR * GENDER	4.519	3	1.506	1.597	.189
TIME * COLOR * GENDER	8.559	24	.357	.378	.997
Error	475.375	504	.943		
Corrected Total	668.234	575			

Table 5.3 ANOVA tests on Vection Rating

Source	Sum of Squares	df	Mean Square	F	Sig.
TIME	163.563	8	20.445	22.006	.000
COLOR	9.920	3	3.307	2.313	.115
GENDER	3.809	1	3.809	1.153	.314
TIME * COLOR	3.257	24	.136	.146	1.000
TIME * GENDER	4.438	8	.555	.597	.781
COLOR * GENDER	3.097	3	1.032	1.111	.344
TIME * COLOR * GENDER	6.465	24	.269	.290	1.000
Error	468.250	504	.929		
Corrected Total	662.000	575			

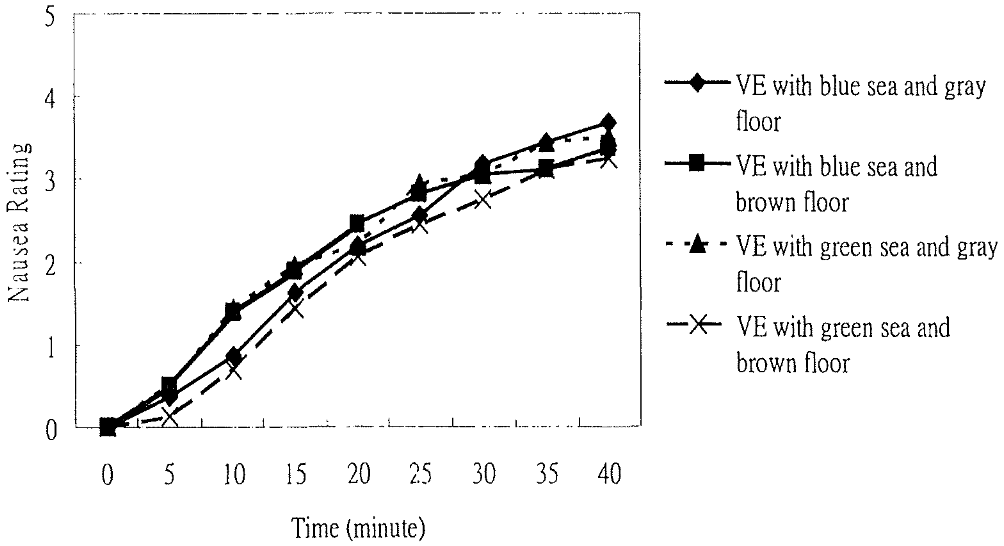


Figure 5.5 Effects of duration of exposure on nausea rating for the 4 virtual environments

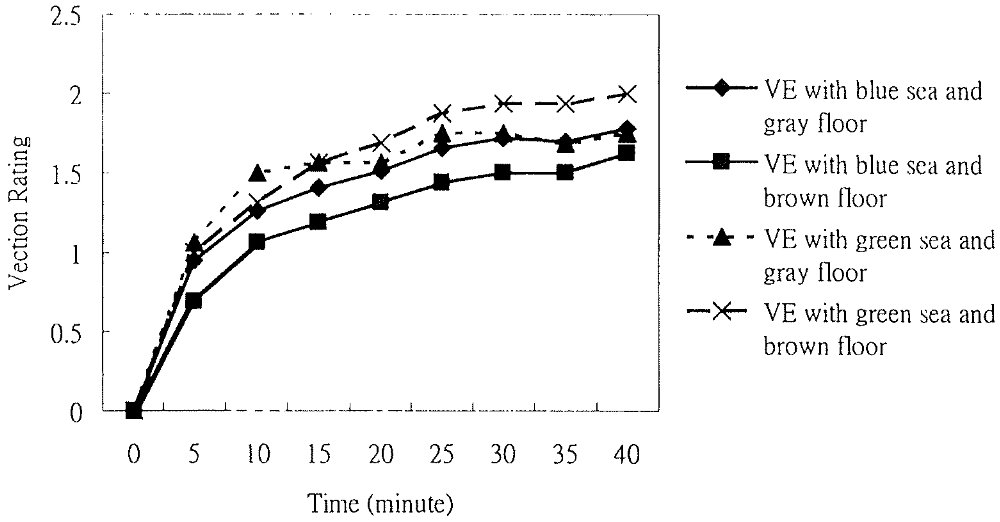


Figure 5.6 Effects of duration of exposure on vection rating for the 4 virtual environments

Table 5.4 Student-Newman-Keuls test on the effect of exposure time on nausea and vection ratings

NAUSEA RATING

SNK Grouping					TIME	N	Nausea Rating
A					0 min	64	.0000
A					5 mins	64	.3750
	B				10 mins	64	1.0938
	B	C			15 mins	64	1.7188
		C	D		20 mins	64	2.2188
			D	E	25 mins	64	2.6875
				E	30 mins	64	3.0156
				E	35 mins	64	3.2813
				E	40 mins	64	3.4531

VECTION RATING

SNK Grouping				TIME	N	Vection Rating
A				0 min	64	.0000
	B			5 mins	64	.9531
	B	C		10 mins	64	1.2656
		C	D	15 mins	64	1.4063
		C	D	20 mins	64	1.5156
		C	D	25 mins	64	1.6563
		C	D	30 mins	64	1.7031
		C	D	35 mins	64	1.7188
			D	40 mins	64	1.7813

5.4.2. Simulator Sickness Questionnaire (SSQ)

Figure 5.7 shows the results of the four scores of Simulator Sickness Questionnaire with respect to the four virtual environments. Statistical tests results are presented in Table 5.5 which shows no significant difference on all SSQ scores for the four virtual environments with different color and gender ($p > 0.1$).

Table 5.5 ANOVA tests on the four scores of SSQ

Dependent Variable: Nausea-related subscore

Source	Sum of Squares	df	Mean Square	F	Sig.
COLOR	4509.340	3	1503.113	1.257	.298
GENDER	1548.619	1	1548.619	1.295	.260
COLOR * GENDER	2598.097	3	866.032	.724	.542
Error	66973.161	56	1195.949		
Corrected Total	75629.218	63			

Dependent Variable: Oculomotor-related subscore

Source	Sum of Squares	df	Mean Square	F	Sig.
COLOR	2219.253	3	739.751	.772	.515
GENDER	1037.806	1	1037.806	1.083	.303
COLOR * GENDER	1095.263	3	365.088	.381	.767
Error	53664.278	56	958.291		
Corrected Total	58016.600	63			

Dependent Variable: Disorientation-related subscore

Source	Sum of Squares	df	Mean Square	F	Sig.
COLOR	4614.062	3	1538.021	.643	.591
GENDER	5340.686	1	5340.686	2.232	.141
COLOR * GENDER	302.760	3	100.920	.042	.988
Error	133989.466	56	2392.669		
Corrected Total	144246.974	63			

Dependent Variable: Total Score

Source	Sum of Squares	df	Mean Square	F	Sig.
COLOR	3960.895	3	1320.298	.909	.442
GENDER	2596.667	1	2596.667	1.788	.187
COLOR * GENDER	637.091	3	212.364	.146	.932
Error	81322.158	56	1452.181		
Corrected Total	88516.811	63			

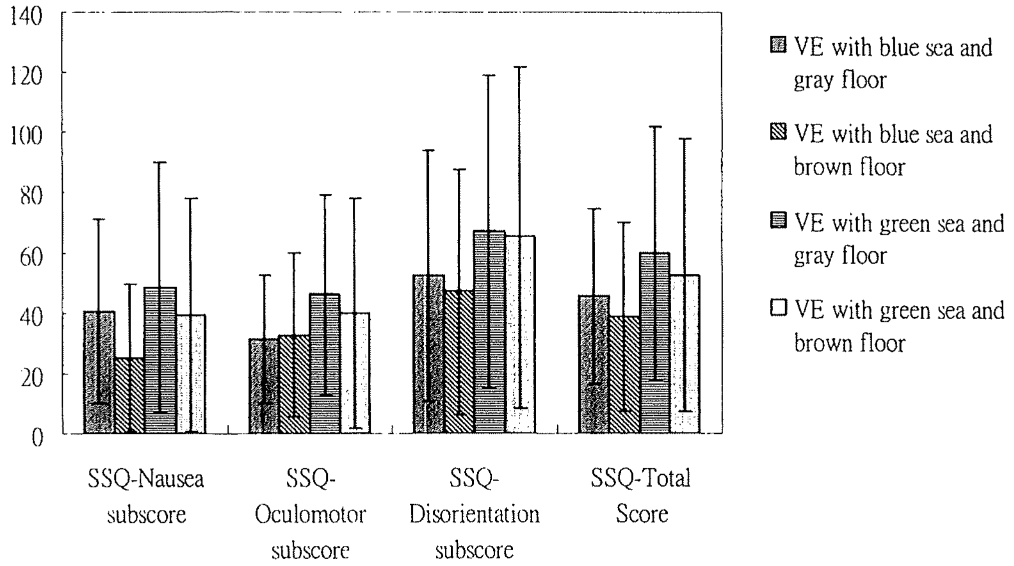


Figure 5.7 Simulator Sickness Questionnaire scores versus the 4 virtual environments (Mean score with ±1 standard deviation)

5.4.3. Postural Tests

Similar to experiment 1, the balance time is used as reference, statistical tests showed that there is no significant difference ($p>0.05$) among the four trials of the SR tests and the three trials of the SOPL and SONL tests. The root-mean-square movements of the head position in the six directions (fore-and-aft, lateral, vertical, roll, pitch and yaw) during the three static postural tests also give the same results. Hence, there is no significant learning effect among the trials. So all the data of the four trials of SR test and the three trials of SOPL and SONL tests were combined in the latter calculations.

Statistic analyses showed that there is no significant difference between the pre-exposure and post-exposure measurements, including balancing time and head deviations in different axes (Table 5.6). The plot the r.m.s. deviation of head position is shown in Appendix G.

Table 5.6 ANOVA test on balancing time of the three postural tests. (pre-exposure – post-exposure)

Dependent Variable: SR test

Source	Sum of Squares	df	Mean Square	F	Sig.
SF	377.125	4	94.281	.752	.560
GENDER	7.082	1	7.082	.056	.813
SF * GENDER	713.759	4	178.440	1.423	.235
Error	8775.475	70	125.364		
Corrected Total	9873.441	79			

Dependent Variable: SOPL test

Source	Sum of Squares	df	Mean Square	F	Sig.
SF	96.716	4	24.179	.892	.474
GENDER	14.532	1	14.532	.536	.467
SF * GENDER	241.025	4	60.256	2.222	.075
Error	1898.481	70	27.121		
Corrected Total	2250.754	79			

Dependent Variable: SONL test

Source	Sum of Squares	df	Mean Square	F	Sig.
SF	373.559	4	93.390	2.387	.059
GENDER	3.052	1	3.052	.078	.781
SF * GENDER	295.750	4	73.938	1.890	.122
Error	2738.432	70	39.120		
Corrected Total	3410.793	79			

5.5. Discussion

From the results of this experiment, color showed no significant effects on the levels of cybersickness and vection. This agrees with the theory of two visual systems theory by Schneider (1967, 1967a) which claims that the ambient vision, which is responsible for detecting motion, is insensitive to color.

The hypotheses of insignificant effect of gender, significant effect of duration of exposure on levels of cybersickness are verified again in experiment 2. With the increase in duration of exposure, we also found out the there may also be a threshold for the duration of exposure. It is shown from the results of experiment 2 that beyond 25 minutes of exposure up to 30 minutes, nausea rating would no longer increase significantly.

Chapter 6. Cybersickness in virtual environments with different average spatial frequencies (Experiment 2)

6.1. Objectives & hypotheses

The objective of this experiment is to investigate the effects of spatial frequency on the levels of cybersickness. To compare with the previous experiment from So et al. (2001) which uses three metropolitan city virtual environments, having an average radial spatial frequency range from 0.018cpd to 0.261cpd (Figure 6.1), another set of virtual environments with a sea-front scenery was built. Moreover, the range of average radial spatial frequency was extended. The five virtual environments used in this experiment have an average radial spatial frequency range from 0.002cpd to 0.413cpd (Figure 6.2). It is not further extended beyond 0.413cpd because it was feared that a virtual environment with an extremely high average radial spatial frequency may become unnatural (Appendix H). ANOVA test results showed that their average radial spatial frequencies are different ($p<0.005$) and Student-Newman-Keuls (SNK) showed that they are in different groups (Table 6.1).

Average Radial Spatial Frequency =

0.018cpd 0.083cpd 0.311cpd

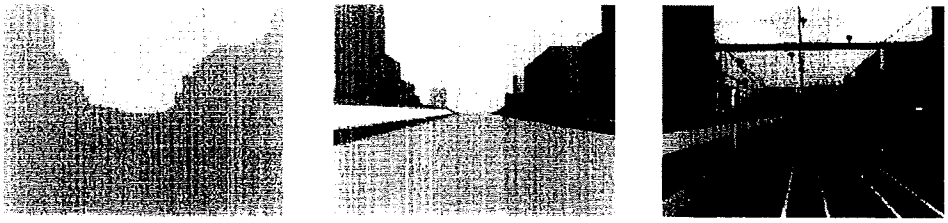


Figure 6.1 Snapshots of the 3 metropolitan city virtual environments used in previous research (So, et al., 2001) from the same view angle and their corresponding average radial spatial frequencies.

Table 6.1 Statistical tests on the average radial spatial frequencies

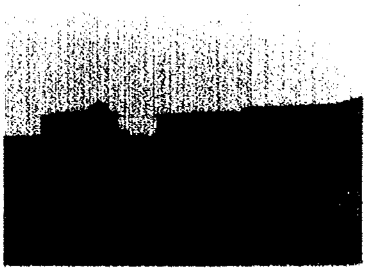
ANOVA test

Dependent Variable: Average Radial Spatial Frequency

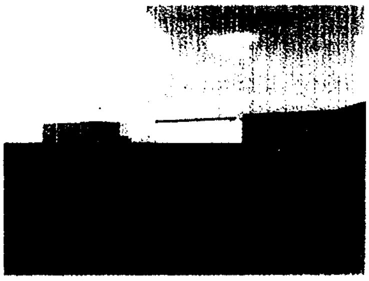
Source	Sum of Squares	df	Mean Square	F	Sig.
LEVEL5	3.846	4	.962	150.596	.000
Error	1.296	203	6.385E-03		
Corrected Total	5.143	207			

Student-Newman-Keuls test

SNK grouping	VE	N	Average Radial Spatial Frequency
A	VE 1	16	0.002cpd
B	VE 2	36	0.076cpd
C	VE 3	57	0.129cpd
D	VE 4	47	0.213cpd
E	VE 5	52	0.413cpd

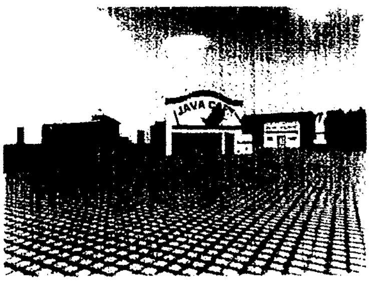


Average Radial Spatial Frequency
= 0.002 cpd



Average Radial Spatial Frequency
= 0.076 cpd

Average Radial Spatial Frequency
= 0.129 cpd



Average Radial Spatial Frequency
= 0.213 cpd

Average Radial Spatial Frequency
= 0.413 cpd

Figure 6.2 Snapshots of the 5 sea-front virtual environments used in experiment 2 from the same view angle and their corresponding average radial spatial frequencies.

Similar to experiment 1, the spatial frequency of virtual environments and gender are between-subject design while the duration of exposure is a with-in subject design.

According to the results from previous study from So et al. (2001), it is hypothesized that the higher the spatial frequency, the higher the levels of cybersickness that the participants would experience. For the duration of exposure, it is hypothesized that the longer the exposure time, the higher the levels of cybersickness. Gender is again, hypothesized to have no significant effect on the levels of cybersickness.

6.2. Procedures

Eighty Chinese aged between 18 and 27 participated in the experiment. They were randomly assigned to one of the virtual environments with equal number of each gender. They were all healthy with normal eyesight. Color blindness test is conducted before the experiment to ensure they do not have color blindness. They were paid $50/hr for their time.

Upon arrival to the experiment, all participants were asked to fill in the pre-exposure Simulator Sickness Questionnaire. Several static postural tests would be conducted afterwards. Participants had to carry out four trials of Sharpened Romberg tests followed by three trials of both Stand On Preferred Leg and Stand On Non-preferred Leg tests with alternating order. The measurements taken for the postural tests are the time that they can balance themselves and the deviation of their heads during the tests. They would then assign randomly to one of the virtual environments. The exposure time is reduced to 30 minutes, comparing to experiment 1. This is because it is found from experiment 1 that nausea rating and vection rating would not significantly increase after 25-minute of virtual environment exposure.

In the virtual environment, the viewpoint was moved according to a pre-determined path. The main axis of movement is the fore-and-aft axis, i.e. the main movement is moving forward. To increase the interaction with the virtual environment and to make the participants more involved in it, the participants were asked to turn their heads for every 30 second. These movements are suggested to have no effect on levels of cybersickness as the viewpoint was moving according to the movement of the head. Therefore, there is no conflict between the stimuli given to the vestibular and visual systems. Hence, from the sensory re-arrangement theory, it would not cause any sickness.

During the 30-minute virtual environment exposure, participants would be asked for their sickness based on the 7-point nausea rating (Golding & Kerguelen, 1992) and their feeling of being moving based on the 4-point vection rating (Appendix F) (Hettinger et al, 1990) in every 5 minutes intervals. On exit to the virtual environment, a post-exposure Simulator Sickness Questionnaire would be given to the participants and all the static postural tests would be conducted again.

6.3. Apparatus

A Virtual Research VR4 LCD Head-Mounted Display (HMD) with a field-of-view of $48^{\circ} \times 36^{\circ}$ was used to present the virtual environments. All the virtual environments were rendered with the dVISE software in Silicon Graphic ONXY II InfiniteReality Workstation with frame rate of 30 frames per second. Polhemus 3-Space magnetic tracker was used to measure the head position and orientation during the virtual reality simulation. Another Polhemus 3-Space magnetic tracker was fixed on the heads of the participants using a earmuff and it was used, with the program developed with the WorldToolKit® software, to keep track with the head movement of the participants throughout the postural tests.

6.4. Results

6.4.1. Nausea Rating and Vection Rating

Table 6.2 and 6.3 show the ANOVA test results of the effect of different factors on nausea rating and vection ratings. Exposure duration was found significantly affecting the nausea rating and vection rating ($p<0.05$). Figure 6.3 and 6.4 show the graph of nausea rating and vection rating versus duration of exposure. Student-Newman-Keuls test results showed in Table 6.4 gives similar results as those in experiment 1. Nausea rating increase significantly from 0 minutes to around 25 minutes. Vection rating, on the other hand, increase significantly from 0 minute to around 10 minutes. From observation from the graph, both ratings seems continue increasing up to 40-minute of VE exposure, but the increment were not significant.

Table 6.2 ANOVA tests on Nausea Rating

Dependent Variable: Nausea Rating

Source	Sum of Squares	df	Mean Square	F	Sig.
TIME	507.100	6	84.517	33.351	.000
GENDER	1.029	1	1.029	.406	.524
SF	171.132	4	42.783	16.882	.000
TIME * GENDER	7.421	6	1.237	.488	.817
TIME * SF	67.168	24	2.799	1.104	.334
GENDER * SF	2.704	4	.676	.267	.899
TIME * GENDER * SF	13.096	24	.546	.215	1.000
Error	1241.750	490	2.534		
Corrected Total	2011.400	559			

Table 6.3 ANOVA tests on Vection Rating

Dependent Variable: Vection rating

Source	Sum of Squares	df	Mean Square	F	Sig.
TIME	94.861	6	15.810	19.712	.000
GENDER	2.064	1	2.064	2.574	.109
SF	5.357	4	1.339	1.670	.156
TIME * GENDER	.611	6	.102	.127	.993
TIME * SF	6.193	24	.258	.322	.999
GENDER * SF	10.114	4	2.529	3.153	.014
TIME * GENDER * SF	5.336	24	.222	.277	1.000
Error	393.000	490	.802		
Corrected Total	517.536	559			

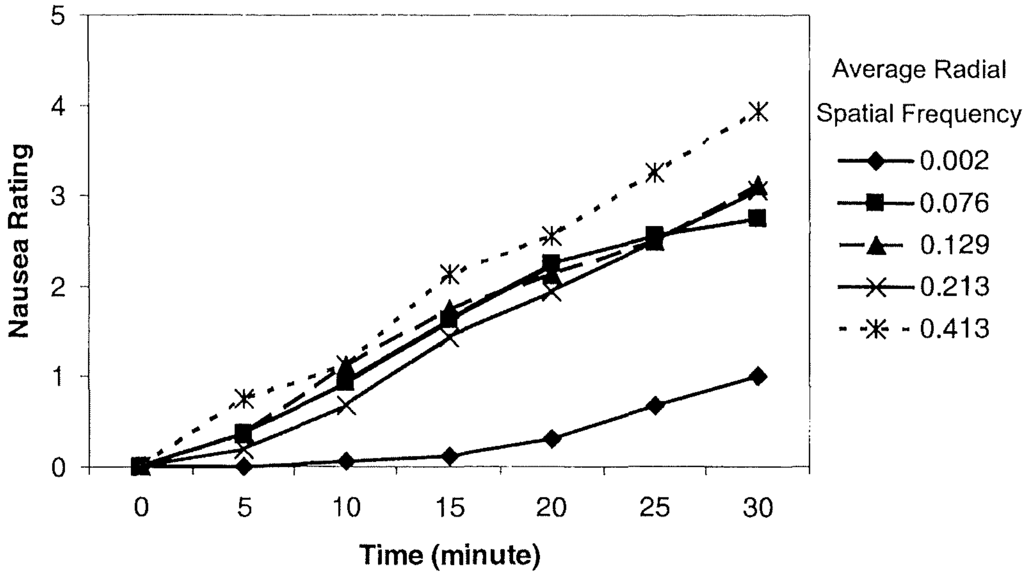


Figure 6.3 Nausea rating versus Duration of exposure

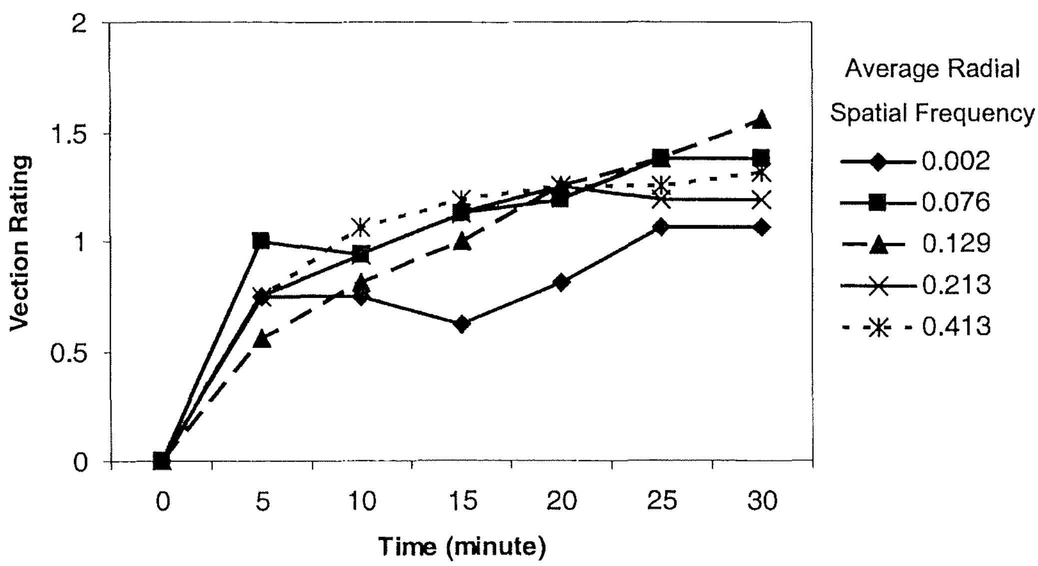


Figure 6.4 Vection rating versus Duration of exposure

Table 6.4 Student-Newman-Keuls test on the effect of exposure time on nausea and vection ratings

NAUSEA RATING

SNK grouping					Duration of exposure	N	Nausea rating
A					0 min	80	.0000
A	B				5 mins	80	.3375
	B				10 mins	80	.7875
		C			15 mins	80	1.4125
		C	D		20 mins	80	1.8375
			D	E	25 mins	80	2.3000
				E	30 mins	80	2.7750

VECTION RATING

SNK Grouping				Duration of exposure	N	Vection Rating
A				0 min	80	0.000
	B			5 mins	80	0.7625
	B	C		10 mins	80	0.9000
	B	C	D	15 mins	80	1.0125
		C	D	20 mins	80	1.15
		C	D	25 mins	80	1.25
			D	30 mins	80	1.3

From the ANOVA test results, gender showed no significant effect on nausea rating and vection rating. This agrees with the hypothesis that gender has no significant effect on cybersickness. ($p>0.5$ for nausea; $p>0.1$ for vection).

Figure 6.5 and 6.6 show the nausea rating and vection rating versus the spatial frequency at different time of exposure. Investigating the effect of spatial frequency, it is found that there is no significant difference on vection ratings

(Table 6.3). In contrast, Student-Newman-Keuls test showed that nausea rating increased significantly with spatial frequency increased from 0.002cpd to 0.076cpd. From 0.076cpd to 0.413cpd, it becomes statistically the same (Table 6.5).

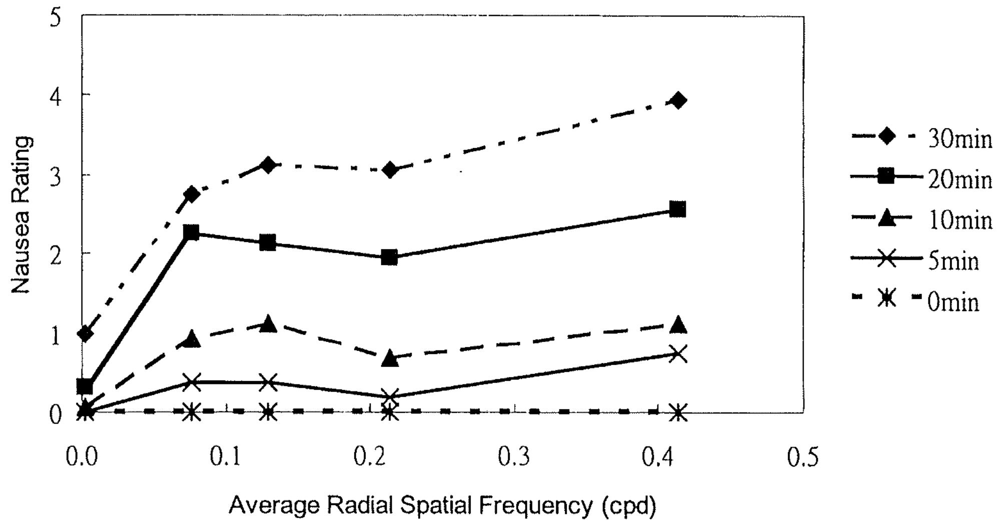


Figure 6.5 Effect of spatial frequency on nausea rating at different time of virtual environment exposure

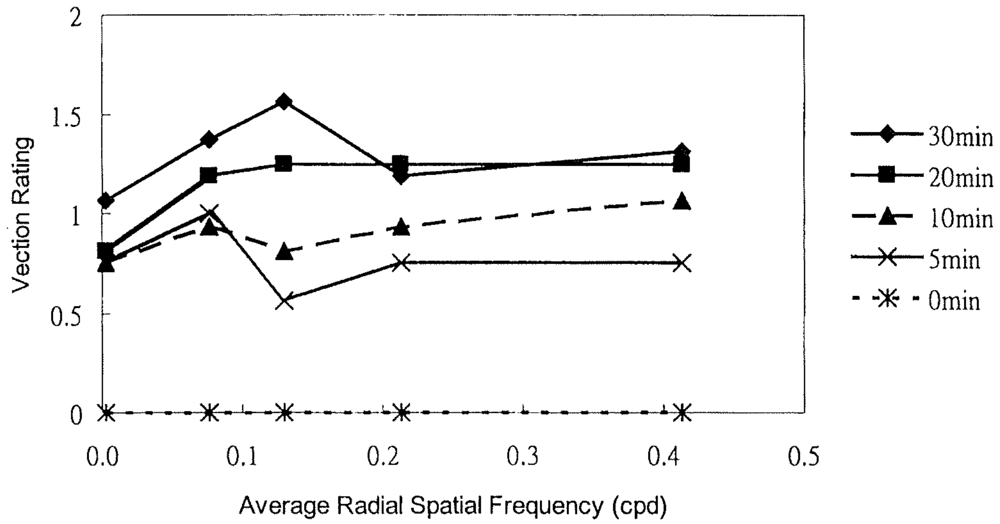


Figure 6.6 Effect of spatial frequency on vection rating at different time of virtual environment exposure

Table 6.5 Student-Newman-Keuls test on the effect of spatial frequency on nausea and vection rating

SNK grouping		Average Radial Spatial Frequency	N	Nausea Rating
A		0.002	112	.3125
	B	0.068	112	1.5000
	B	0.113	112	1.5714
	B	0.220	112	1.4018
	B	0.412	112	1.9643

From the ANOVA table of vection rating (Table 6.3), it is also found that the interactions between spatial frequency and gender are also having significant effect on vection rating ($p<0.02$). Interaction plot in Figure 6.7 shows that there is interaction between these two factors.

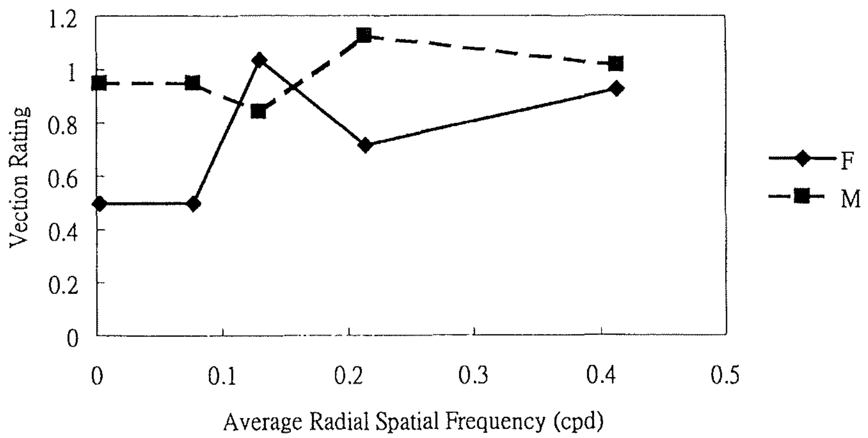


Figure 6.7 Interaction plot between spatial frequency and gender on vection rating

Possible reason for this could be due to the duration of exposure. Table 6.6 shows the ANOVA tables on vection rating at different duration of VE exposure, from 5min to 30min of exposure (Note: vection ratings for all subjects at 0min are 0, therefore, statistical tests is not applicable). They all show that the interaction between spatial frequency and gender is not significantly affecting vection rating (p>0.3).

Table 6.6 AVNOA tables on vection rating at exposure time of 5min, 10min, 15min, 20min, 25min and 30min

Dependent Variable: Vection at 5min

Source	Sum of Squares	df	Mean Square	F	Sig.
SF	1.550	4	.388	.541	.706
GENDER	.613	1	.613	.855	.358
SF * GENDER	2.200	4	.550	.768	.550
Error	50.125	70	.716		
Corrected Total	54.487	79			

Dependent Variable: Vection at 10min

Source	Sum of Squares	df	Mean Square	F	Sig.
SF	.950	4	.238	.270	.896
GENDER	.450	1	.450	.512	.477
SF * GENDER	4.300	4	1.075	1.224	.309
Error	61.500	70	.879		
Corrected Total	67.200	79			

Dependent Variable: Vection at 15min

Source	Sum of Squares	df	Mean Square	F	Sig.
SF	3.300	4	.825	.887	.477
GENDER	.312	1	.312	.336	.564
SF * GENDER	4.250	4	1.062	1.142	.344
Error	65.125	70	.930		
Corrected Total	72.988	79			

Dependent Variable: Vection at 20min

Source	Sum of Squares	df	Mean Square	F	Sig.
SF	2.325	4	.581	.588	.673
GENDER	5.000E-02	1	5.000E-02	.051	.823
SF* GENDER	2.575	4	.644	.651	.628
Error	69.250	70	.989		
Corrected Total	74.200	79			

Dependent Variable: Vection at 25min

Source	Sum of Squares	df	Mean Square	F	Sig.
SF	1.125	4	.281	.282	.889
GENDER	.800	1	.800	.803	.373
SF * GENDER	1.325	4	.331	.332	.855
Error	69.750	70	.996		
Corrected Total	73.000	79			

Dependent Variable: Vection at 30min

Source	Sum of Squares	df	Mean Square	F	Sig.
SF	2.300	4	.575	.521	.721
GENDER	.450	1	.450	.408	.525
SF * GENDER	.800	4	.200	.181	.947
Error	77.250	70	1.104		
Corrected Total	80.800	79			

6.4.2. Simulator Sickness Questionnaire (SSQ)

Table 6.7 showed the ANOVA results of the effects of different factors on the four SSQ scores. Gender was found, agree with the hypothesis, having no significantly effect on all the SSQ scores (p > 0.4).

Table 6.7 ANOVA tests on the four scores of SSQ

Dependent Variable: Nausea-related subscore

Source	Sum of Squares	df	Mean Square	F	Sig.
GENDER	550.620	1	550.620	.575	.451
SF	11235.382	4	2808.846	2.933	.027
GENDER * SF	177.473	4	44.368	.046	.996
Error	67030.043	70	957.572		
Corrected Total	78993.518	79			

Dependent Variable: Oculomotor-related subscore

Source	Sum of Squares	df	Mean Square	F	Sig.
GENDER	183.860	1	183.860	.371	.544
SF	4072.222	4	1018.056	2.057	.096
GENDER * SF	326.065	4	81.516	.165	.956
Error	34646.209	70	494.946		
Corrected Total	39228.357	79			

Dependent Variable: Disorientation-related subscore

Source	Sum of Squares	df	Mean Square	F	Sig.
GENDER	784.754	1	784.754	.462	.499
SF	15758.052	4	3939.513	2.322	.065
GENDER * SF	353.624	4	88.406	.052	.995
Error	118778.803	70	1696.840		
Corrected Total	135675.233	79			

Dependent Variable: Total Score

Source	Sum of Squares	df	Mean Square	F	Sig.
GENDER	548.314	1	548.314	.531	.469
SF	11239.037	4	2809.759	2.722	.036
GENDER * SF	196.526	4	49.131	.048	.996
Error	72263.439	70	1032.335		
Corrected Total	84247.315	79			

Figure 6.8 showed the change of four SSQ scores (Nausea Subscore, Oculomotor Subscore, Disorientation Subscore and Total Score) with respect to the average radial spatial frequency in the virtual environment. Similar to the nausea rating, Student-Newman-Keuls tests showed that the nausea-related subscore and total score of SSQ significantly increased from 0.002cpd to around 0.076cpds ($p<0.05$). Beyond around 0.076cpd, they become statically the same (Table 6.8). The other two SSQ scores, the oculomotor-related subscore and the disorientation-related subscore, did not show significant difference with spatial frequency increase from 0.002cpd to 0413cpd. This may be because nausea-related subscore is more sensitive to the spatial frequency as nausea rating also show similar relationship.

Table 6.8 Student-Newman-Keuls

SSQ – Nausea-related subscore

SNK grouping		Average Radial Spatial Frequency	N	SSQ – Nausea-related subscore
A		0.002	16	5.9625
	B	0.068	16	29.2163
	B	0.113	16	35.1788
	B	0.220	16	35.1788
	B	0.412	16	38.7562

SSQ - Total Score

SNK grouping		Average Radial Spatial Frequency	N	SSQ – Total Score
A		0.002	16	7.7138
	B	0.068	16	32.4913
	B	0.113	16	35.9975
	B	0.220	16	37.6338
	B	0.412	16	40.4388

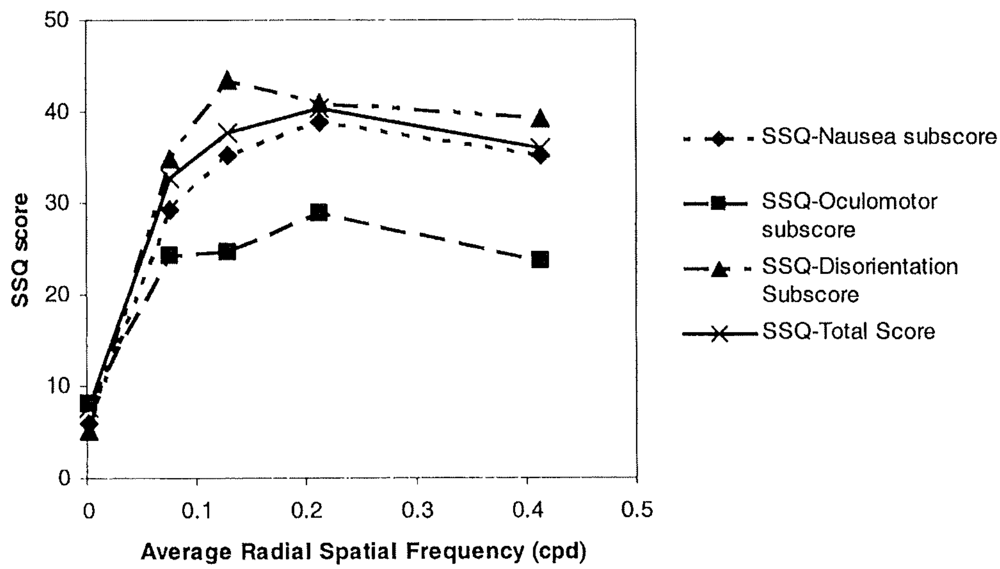


Figure 6.8 Effect of spatial frequency on the scores of the simulator sickness questionnaire

6.4.3. Postural Tests

Using the balance time as a reference, statistical tests showed that there is no significant difference ($p>0.05$) among the four trials of the SR tests and the three trials of the SOPL and SONL tests. The root-mean-square movements of the head position in the six directions (fore-and-aft, lateral, vertical, roll, pitch and yaw) during the three static postural tests also give the same results. Hence, there is no significant learning effect among the trials. So all the data of the four trials of SR test and the three trials of SOPL and SONL tests were combined in the latter calculations.

However, there is no obvious trend found from the results of the postural tests (Appendix I). Statistic analyses showed that there is no significant difference between the pre-exposure and post-exposure measurements, including balancing time and head deviations in different axes (Table 6.9). Nevertheless, most of the results from different axes showed a larger head deviation for the post-exposure measurements.

Table 6.9 ANOVA test on the balancing time of the three postural tests. (pre-exposure – post-exposure)

Dependent Variable: SR test

Source	Sum of Squares	df	Mean Square	F	Sig.
COLOR	1019.188	3	339.729	2.525	.067
GENDER	119.171	1	119.171	.886	.351
COLOR * GENDER	644.002	3	214.667	1.596	.201
Error	7533.894	56	134.534		
Corrected Total	9316.255	63			

Dependent Variable: SOPL test

Source	Sum of Squares	Df	Mean Square	F	Sig.
COLOR	188.517	3	62.839	1.585	.203
GENDER	4.340	1	4.340	.109	.742
COLOR * GENDER	1.001	3	.334	.008	.999
Error	2220.393	56	39.650		
Corrected Total	2414.251	63			

Dependent Variable: SONL test

Source	Sum of Squares	df	Mean Square	F	Sig.
COLOR	79.638	3	26.546	.718	.545
GENDER	69.827	1	69.827	1.889	.175
COLOR * GENDER	170.670	3	56.890	1.539	.214
Error	2069.949	56	36.963		
Corrected Total	2390.084	63			

6.4.4.

6.4.5. Comparison with previous studies

Comparing the results of the previous study (So et al., 2000) and current study, they quite agree with each other in that with higher spatial frequency, participants would have higher level of sickness. The graph with data from both experiments is shown in Figure 6.9.

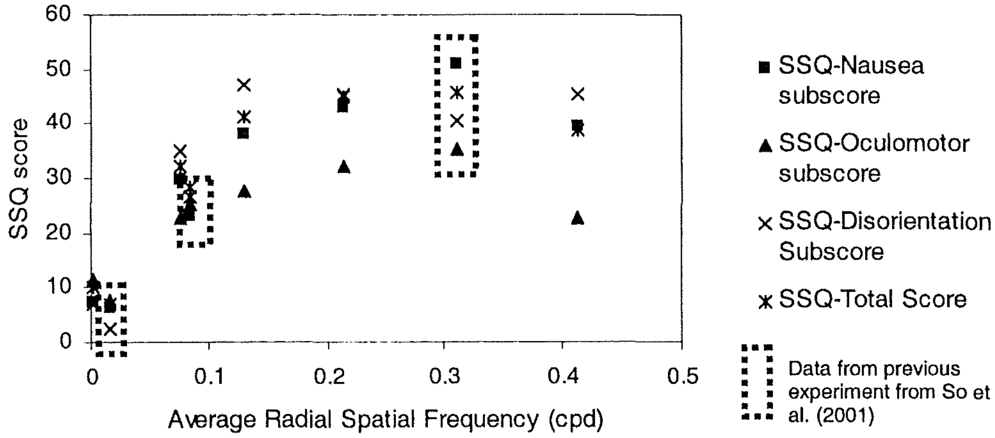


Figure 6.9 Effect of average radial spatial frequency on SSQ scores (results from the previous experiment and this experiment)

6.5. Discussion

The nausea rating results of this study reinforced the findings of previous studies on the effect of exposure time and presence of vection. That is, nausea ratings increase with increased exposure time and are significantly higher among the participants having vection during the virtual environment exposure.

Experiment results showed that gender is not significantly affecting the levels of cybersickness ($p>0.05$). This disagrees with the results by Kennedy et al. (1995) and Kolasinski (1995) which found a higher susceptibility of sickness among female participants. However, it matches with the preliminary results by done by Yoo et al. (1997). One possible reason for that could be because of the nature of the participants. Kennedy et al. (1995) used participants from the US Army who are familiar with the virtual reality simulator while in Yoo et al. (1997) and this study, students and staff from university were invited. The deviation between individuals in US Army would be much less than university students and staff. Therefore, any differences would be much easier to be spot out with Army.

For the effect of spatial frequency, the trend of nausea rating with increasing spatial frequency is quite similar to that with increasing navigation velocity [8]. It keeps increasing until reaching a certain threshold. Beyond that threshold, it becomes statistically the same.

Results from Simulator Sickness Questionnaire show similar trends to those from nausea ratings. But the increasing trend from spatial frequency beyond 0.220cpds in the nausea ratings does not match with the decreasing one in the SSQ scores, even compared to the Nausea subscores. It is likely that the additional symptoms in the SSQ lead to these differences.

Results from postural tests are quite irregular and it is quite difficult to draw a conclusion on the relationship between the postural stability of the participants and other factors. Some improvements or modifications should be introduced when conducting the posture tests in the future. E.g. trained participants may give more significant results in showing the effect of virtual environment exposure (Hamilton et al., 1989). Although there is no significant learning effect found in this study, training could effectively eliminate the effect and let the participants get used to the posture tests. Also, the duration of exposure could be increased in order to amplify the effect on the participants.

The similar results from the previous study by So et al. (2001) and this experiment show that the effect of spatial frequency is consistent in two different types of virtual environment. Moreover, with the results from the extended range of spatial frequency in the current experiment, it is probable that the levels of cybersickness would increase with higher spatial frequency. However, beyond a certain threshold, they would not increase significantly. From the results of the experiment, this threshold is probably around 0.076cpd.

Apart from cybersickness, the rotating drum experiments are another type of visually induced motion sickness. Hu et al. (1997) studied the effects of spatial frequency on motion sickness using the rotating drum. Their results showed that motion sickness peaked when spatial frequency reached 0.067cpd. Comparing the two visually induced motion sickness, experiment results from Hu et al. (1997), previous experiment from So et al. (2001) and experiment 2, we note a similar peak of sickness level at spatial frequency of around 0.076cpd. Figure 6.10 shows the combined graph with the results from the above three experiments.

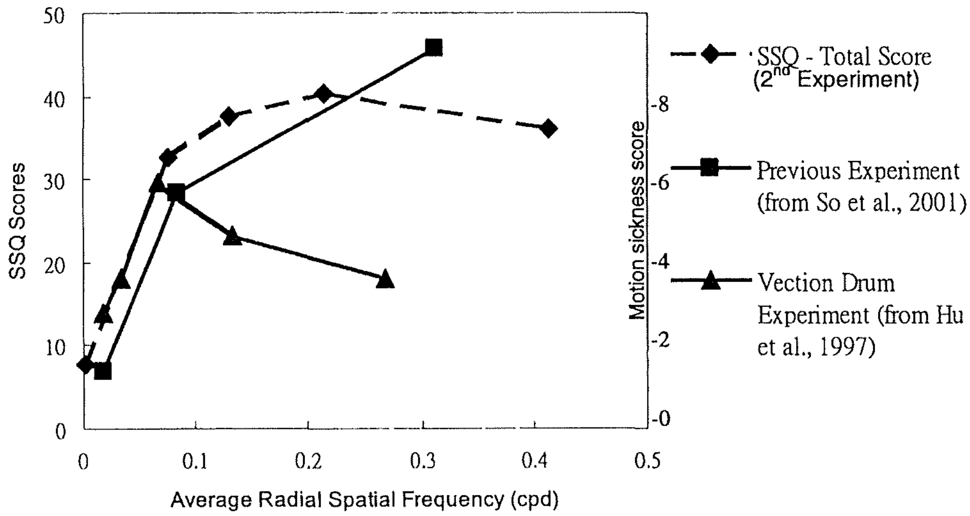


Figure 6.10 Comparison of sickness level in vection drum experiment from Hu et al. (1997) and two virtual environment experiments.

Chapter 7. Overall Discussion & Conclusion

7.1. Discussion

The results from the first experiment showed that color has no significant effect on levels of cybersickness. This validates our assumption that the chrominance factor of the visual stimuli has little effect on cybersickness. Hence, the conversion of color pictures to grayscale ones is reasonable in calculating the spatial frequency of virtual environments and should have no significant effect on our results.

Results from the second experiment showed that with higher spatial frequency in virtual environments, there would be a significant increase in the levels of cybersickness. This result is similar in two different types of virtual environments. Also, similar to the result from So et al. (2001a) which studied the effects of navigation speed, there seems to exist a threshold of spatial frequency at around 0.076cpd above which further increases up to 0.413cpd would not significantly add to the levels of cybersickness.

Comparing the results with the rotating drum experiment done by Hu et al. (1997), who found motion sickness peaked when spatial frequency reach 0.067cpd, the two visually induced instances of motion sickness showed a similar peak at a spatial frequency equaling around 0.076cpd.

Moreover, the duration of exposure is found to be a significant factor affecting levels of cybersickness. The insignificant increase in nausea rating after 25 minutes of exposure for up to 40 minutes suggested the possibility of a threshold where further exposure time would not increase the cybersickness experienced.

Both experiments show no significant effect of gender on the levels of cybersickness. This agrees with most of the past research although the higher susceptibility of the male in experiment 2 disagrees with some of the research.

However, in both experiments, we failed to discover any significant effects from the postural test results. One possible reason for this may be because of the high inter and intra subject variability, which was also found by Cobb (1999) when analyzing the data from the Tandem Posture test. To reduce the intra-subject variability, training of the posture tests could be given to reduce the differences between trials. To reduce the inter-subject variability, screening of subjects could be introduced. Those who fail to hold their posture for the required duration before the virtual environment exposure would be excluded from the experiment and this could ensure all the subjects are quite able to control their posture under normal conditions.

In addition, the algorithm for finding the optimal number of snapshots to be sampled is proposed in this research. It is verified by using the data from two virtual environments. Along with the introduction of the degradation of sampled snapshots, the quantification of the scene complexity can be enhanced, which allows us to have a more representative value for the visual stimuli given to the users of virtual reality systems while the labor of capturing snapshots is reduced.

Scene complexity has been defined as an important component in the visual stimulus. The results from this research can contribute to the development of Cybersickness Dose Value (CSDV) introduced by So (1999). The effects of spatial frequency and color proved the importance of visual stimulus on cybersickness while the sampling algorithm helped to reduce the workload in further research on other aspects of visual stimulus.

7.2. Conclusion

The results of this research provide a better insight for the effects of visual stimuli on the levels of cybersickness. Reported levels of cybersickness were found to increase when the radial spatial frequency of a virtual environment increases from 0.002cpd to 0.076cpd. When the radial spatial frequency increases beyond 0.076cpd to 0.413cpd, the levels of cybersickness remain unchanged. Color of a virtual environment, on the other hand, was found to have no significant effect on the levels of cybersickness. The threshold of 0.076cpd agrees with previous studies concerning the levels of sickness induced in participants viewing a rotating drum. The results were also found to be consistent with the two visual systems theory (Schneider, 1967; Schneider, 1967a).

A previous study from So et al. (2001) sampled the snapshots at a rate of two pictures per second in order to obtain enough samples to calculate the average radial spatial frequency of a VR simulation. This thesis introduces a sampling algorithm that can reduce the number of snapshots. With this algorithm, the numbers of snapshots have been reduced from 3600 to below 60 for two different virtual environments.

Chapter 8. Limitations and Future work

Comparison between the previous and current experimental results showed that an increase in spatial frequency would lead to increase in levels of cybersickness until the threshold of spatial frequency of about 0.076cpd is reached. However, as the navigation speeds in the previous and current experiments are different, there is a possibility that it may affect the results. So et al. (2001a) found that an increase in navigation speed would also increase the levels of cybersickness. Therefore a study investigating the effects of spatial frequency, navigation speed and their interaction with cybersickness is recommended.

The verification of the insignificant effect of color on levels of cybersickness reinforces the use of grayscale during the calculation of scene complexity. According to the two visual systems theory, the ambient vision, which is responsible for the motion perception, is not sensitive to the high spatial frequency, i.e. the detailed information. Hence an experiment would be recommended to verify this assumption. This could be done by applying a blurring effect to the virtual environment. A blurring effect could make the detailed information within the virtual environment become unclear (Figure 8.1). Most of the graphic-editing software has this blurring function, e.g. Paint Shop Pro® from Jasc Software®, Eden Prairie, USA. Therefore, it is similar to a high frequency filter which cuts off the high frequency inside the virtual environment. If the level of cybersickness associated with the clear and blurred virtual environments are similar, then the effect of detailed information, i.e. the high frequency, would be proved to have no significant effect and the use of combined method would be verified.

Figure 8.1 Virtual environment from experiment 1 and virtual environment after applying blurring effect

A sampling algorithm for finding the optimal number of snapshots to be captured in calculating the spatial frequency of a virtual environment is proposed in this thesis. This algorithm has been verified by two different types of virtual environments. However, both virtual environments used in verification are outdoor ones. It is suspected that an indoor virtual environment could be of different variations in spatial frequency from snapshot to snapshot. This is because, for outdoor virtual environments, the sky, a great portion of the environment, naturally would not be too complex or of great variation from area to area. But for indoor environments, the decorations could be of any type and vary a lot from region to region. Hence, further verification is suggested when applying this algorithm to other types of environment such as an indoor environment.

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Appendix A The definitions of the 7-point nausea rating (adopted from Golding & Kerguelen, 1992)

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

Appendix B The calculations in the Simulator Sickness Questionnaire

None = 0

Slight = 1

Moderate = 2

Severe = 3

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

Score

Nausea = [1] $\times$ 9.54

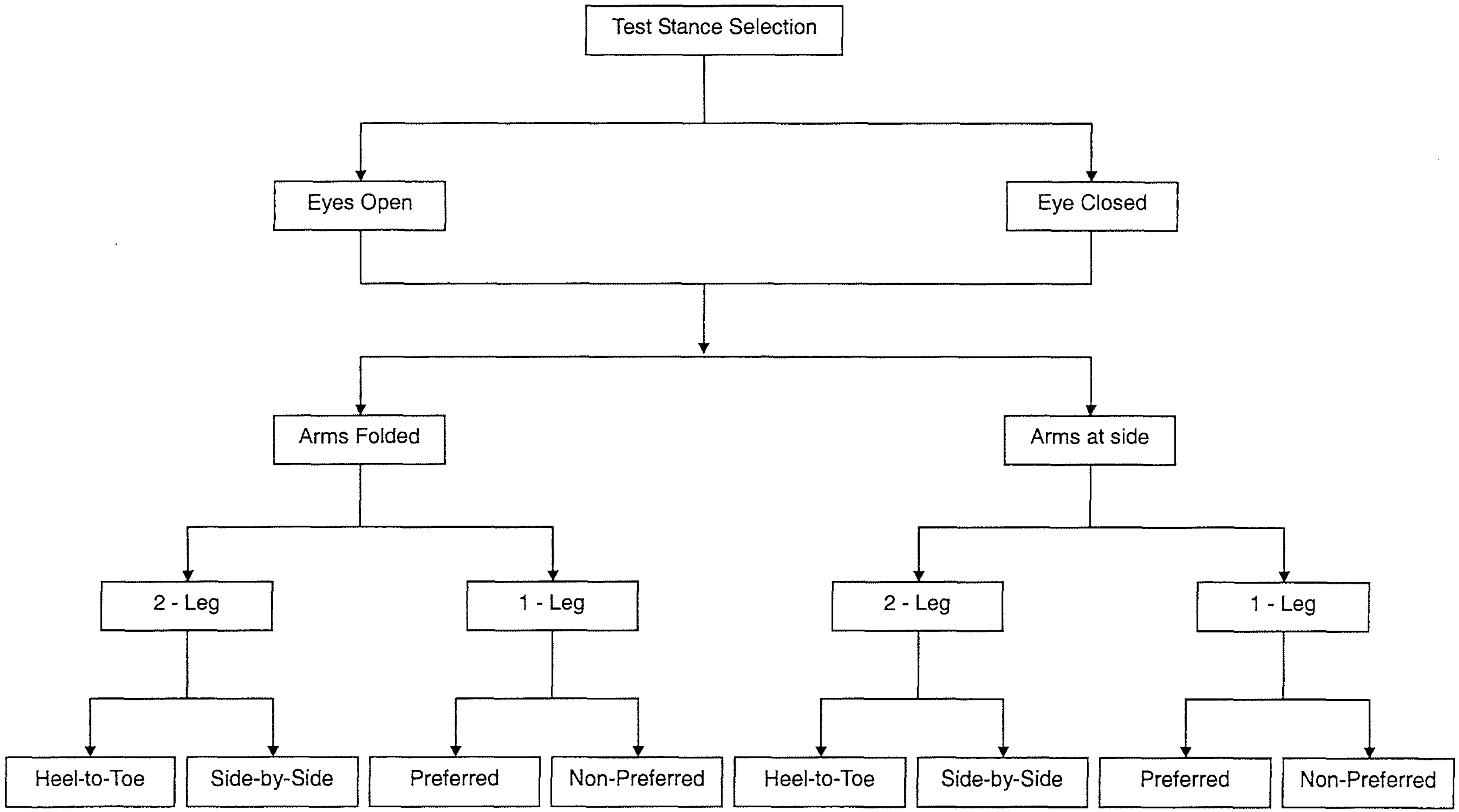
Oculomotor = [2] $\times$ 7.58

Disorientation = [3] $\times$ 13.92

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

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

Appendix C The list of static postures (adopted from Kennedy & Stanney, 1996)



APPENDIX D Two Visual Systems Theory

The two visual systems theory was proposed by Schneider. (Schneider, 1967; Schneider, 1967a). It suggested that visual stimuli are processed differently depending on their characteristics. The different psychophysical and neurological characteristics serve different aspects of the visually controlled behavior. However, the complexity of the neuroanatomical structures in human leave many questions unanswered.

Held (1970), on the other hand, emphasized the functional differences between "two modes of processing spatially distributed information". Leibowitz and Post (1982) adopted this emphasis and suggested the two modes as a focal mode (focal vision) responsible for the detailed information such as object identification and discrimination and an ambient mode (peripheral vision) responsible for spatial localization, orientation and locomotion.

The characteristics of the two visual systems have been studied extensively. Various factors have been found having different effects on focal mode and ambient mode. Leibowitz et al. (1979) found that even a slight refractive error could affect the functions of focal mode as the detailed information is being distorted. On the contrary, as long as a minimal pattern is available, the ambient mode could function efficiently. Since refractive error would greatly affect the high spatial frequency rather the lower ones, it is suspected that focal vision is good at higher spatial frequencies while low spatial frequencies are enough to stimulation the peripheral vision.

Stern et al. (1990) found that a visual field restricted to 15°, i.e. using the focal vision only, greatly reduced the vection-induced motion among experiment participants compared with those using the entire visual field. Andersen and Braunstein (1985) also concluded the failure to induce self-motion in the central vision (up to 30° in diameter). These studies agree with the conclusion of Dichgans and Brandt (1978) that stimulation of the peripheral vision is necessary to induce self-motion while central visual field is specialized for the perception of object motion.

In this research, the characteristics of the two visual systems theory have been applied. The ambient or peripheral vision, which is responsible for spatial orientation and vection, is found by previous studies to be insensitive to color and high spatial frequencies. This characteristic has been used when calculating the average radial spatial frequency of virtual environments (Appendix E).

APPENDIX E Use of Spatial Frequency in measuring scene complexity of virtual environment

Spatial frequency is a measurement of frequency of spatial variations in luminance level (So et al., 2001). The corresponding unit is cycles per degree (cpd), i.e. the number of cycles of changes in luminance level per degree of visual angle. For a given series of luminance changes, the frequencies of spatial variations could be easily extracted by finding the corresponding power spectral density (PSD) functions. This can be calculated by using the Fast Fourier Transform (FFT) operations.

Spatial frequency has been used in measuring the scene complexity of the vection-induced drum experiments (Hu et al., 1997). In applying this in measuring the scene complexity of virtual environment, snapshots from the virtual environment have to be captured.

According to the numerous works of research related to the two visual systems theory (Schneider, 1967; Schneider, 1967a) (Appendix D), it is assumed that color does not significantly affect the levels of cybersickness. Hence, in calculating the spatial frequency of snapshots captured from virtual environments, they were converted to the corresponding grayscale first.

One common method of grayscale conversion is to use the Red Green Blue (RGB) components (Hoffmann, 2002) (Figure E.1). Any color display on a screen can be decomposed into the Red, Green and Blue components. For each component, the value can range from 0 to 255, i.e. having 2^8=256 levels for each color component. For a pixel on a display, a value of 0 means it has a full range of that color while a value of 255 means it lacks that component. Therefore, a color of RGB = [0 0 0] is black and a color of RGB = [255 255 255] is white (Figure E.2).

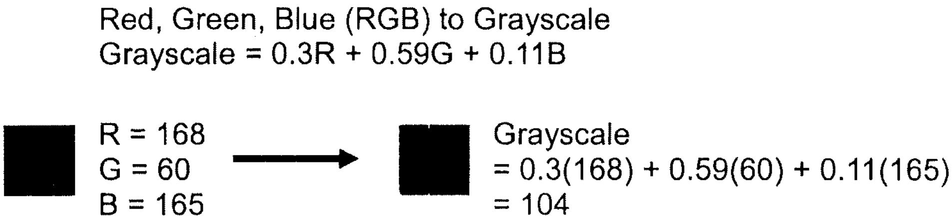


Figure E.1 Algorithm for converting color to grayscale

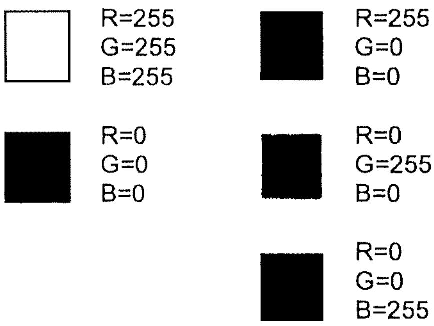


Figure E.2 Illustration of colors represented by RGB code

For each snapshot, there are a certain number of horizontal and vertical lines. Each line can be treated as a series of luminance changes with respect to the change of visual angle. Therefore, we can find the combinations of frequency of luminance changes for a specific line by getting the corresponding PSD (Figure E.3).

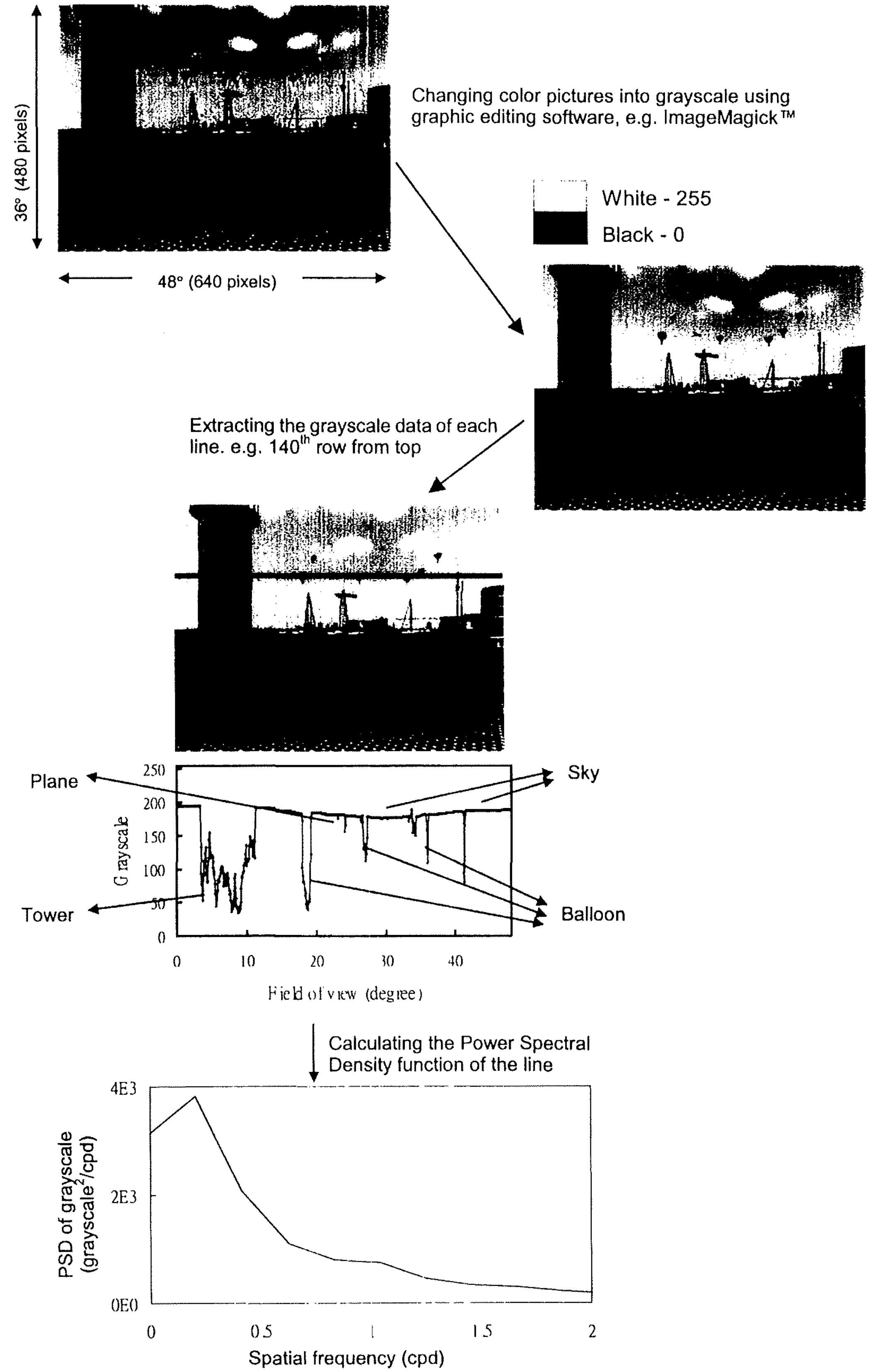


Figure E.3 Extraction of spatial frequency for a line in a sample snapshot from a virtual environment

Though PSD could give the distribution of the spatial frequency from a series of luminance variation, there is no standard method to determine of the dominant spatial frequency. Three methods were proposed by So et al. (2001).

Mean method calculates the average spatial frequency according to the Power Spectral Density (PSD) distribution to represent the frequency of the line. Mode method uses the spatial frequency at which the amount of luminance variations peaked as the representative frequency for the specific line. The combined method calculates the dominant spatial frequency according to the following equation:

Dominant spatial frequency = Average of (frequency at which the spatial frequency PSD has the highest peak + all other frequencies at which the values of spatial frequency PSD is greater than half of the maximum peak).

Figure E.4 shows the dominant spatial frequencies of a PSD using the three proposed methods.

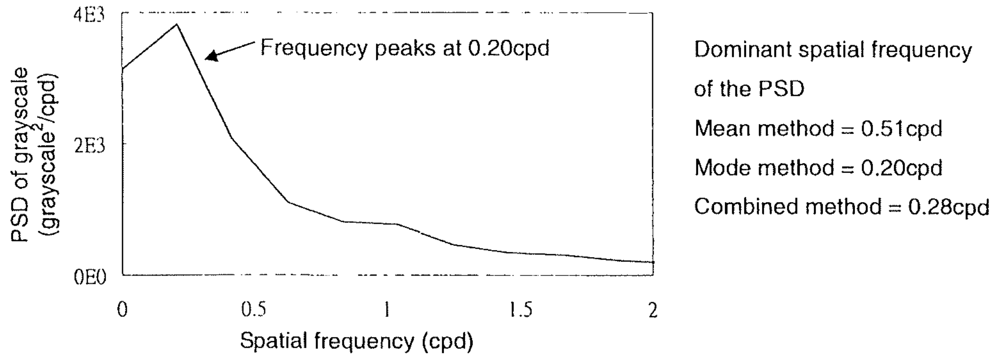
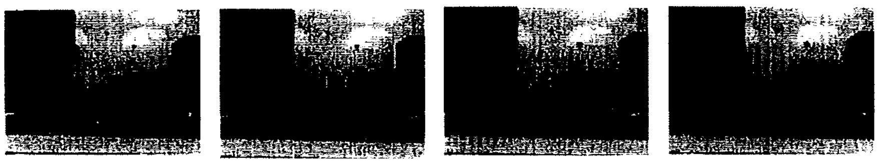


Figure E.4 Determination of dominant spatial frequency using the three proposed methods from So et al. (2001)

Whether one of the above methods is better than the others in representing the dominant spatial frequency is still under investigation. In this research, the combined method is used in determining the spatial frequency of the virtual environment. This choice is based on the assumption of two visual systems theory (Schneider, 1967; Schneider, 1967a) (Appendix D).

According to the two visual systems, the fine details, the high spatial frequency stimuli, should have no significant effects on the levels of vection. Leibowitz et al. (1979) studied the effect of refractive error on vection by introducing the diopter lens. Their results showed that levels of vection is not affected by the refractive error. They concluded that the visual system which is responsible for spatial orientation and vection, i.e. the ambient vision from the two visual systems theory, is not sensitive to the high-frequency of luminance variations or the high spatial frequencies.

As vection is a precondition for cybersickness (Hettinger et al., 1990), it is suspected that high spatial frequency also has no significant effect on the levels of cybersickness. Blurring, which would eliminate the high frequency of the pictures, should have little effect on the scene complexity in order to ensure similar levels of cybersickness. However, the results in So et al. (2001) showed that there is a significant drop in spatial frequency when adopting the mean algorithm (Figure E.5). Hence, mean algorithm may not be a good one for finding the representative spatial frequency of the virtual environment. For the mode algorithm, as it just picks out the frequency with the highest amplitude, it may eliminate the effect of other frequencies which also have high amplitudes. Therefore, in this research, the combined algorithm is used in calculating the spatial frequency in the virtual environments.



Radius=0 (i.e. no blur) Radius=1 Radius=2 Radius=4

SF_{hori} SF_{vert} SF_{hori} SF_{vert} SF_{hori} SF_{vert} SF_{hori} SF_{vert}

Mean : 0.84cpd 0.35cpd 0.26cpd 0.22cpd 0.15cpd 0.18cpd 0.09cpd 0.16cpd

Figure E.5 Spatial frequency measurements for a sample snapshot with and without blurring effects (blurring radius of 0, 1, 2 and 4 using the software Paint Shop Pro®; field-of-view: 48° horizontal × 36° vertical; resolution: 640 pixels × 480 pixels (adopted from So et al., 2001)

After the determination of dominant spatial frequency for each line of luminance change series, the representative spatial frequency for a snapshot in virtual environment could be calculated. For a snapshot of resolution of 640 pixels $\times$ 480 pixels, there will be:

480 horizontal lines $\Rightarrow$ 480 dominant horizontal spatial frequencies

640 vertical lines $\Rightarrow$ 640 dominant vertical spatial frequencies

Therefore, the representative spatial frequencies of a snapshot are:

Horizontal spatial frequency (SF_{hori}) = average of 480 dominant horizontal spatial frequencies

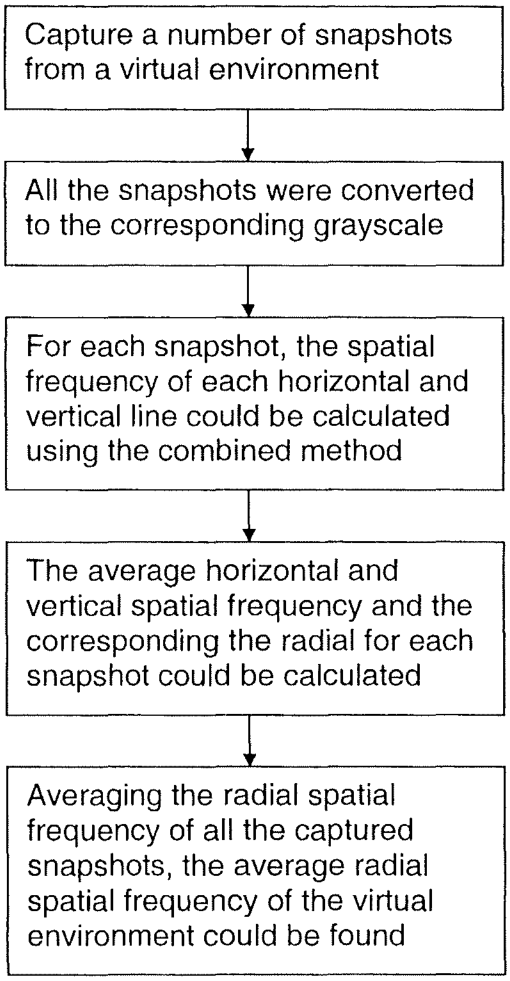
Vertical spatial frequency (SF_{vert}) = 640 dominant vertical spatial frequencies

Apart from horizontal and vertical spatial frequencies, radial spatial frequency is introduced. It is defined as:

Radial spatial frequency (SF_{rad}) = $[SF_{hori}^{2} + SF_{hori}^{2}]^{1/2}$

The use of radial spatial frequency as an index for the scene complexity of snapshots is because it is more logical to the nature of virtual simulation. For most of the virtual simulation, the main axis of movement would be the fore-and-aft axis. Imagine a situation of shining a flashlight at a screen, as the flashlight moves towards or backward the screen (i.e. along the fore-and-aft axis), the spot of light will change its radial dimension. Therefore, the radial spatial frequency may be a better representation for the scene complexity of snapshots from virtual environment.

Capturing a number of snapshots from a virtual environment, e.g. 2 pictures per second in So et al. (2001), the representative spatial frequency for the virtual environment could be calculated by averaging the radial spatial frequency of all the captured snapshots. In this research, the representative spatial frequency for a virtual environment is termed as the average radial spatial frequency. Overall procedures for calculating the scene complexity of a virtual environment using spatial frequency are shown in Figure E.6.



E.6 Procedures for calculating the spatial frequency of a virtual environment using

Appendix F Definition of the 4-point apparent self-motion (vection) rating

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

APPENDIX G Results of postural tests for experiment 1 (Effects of color on levels of cybersickness)

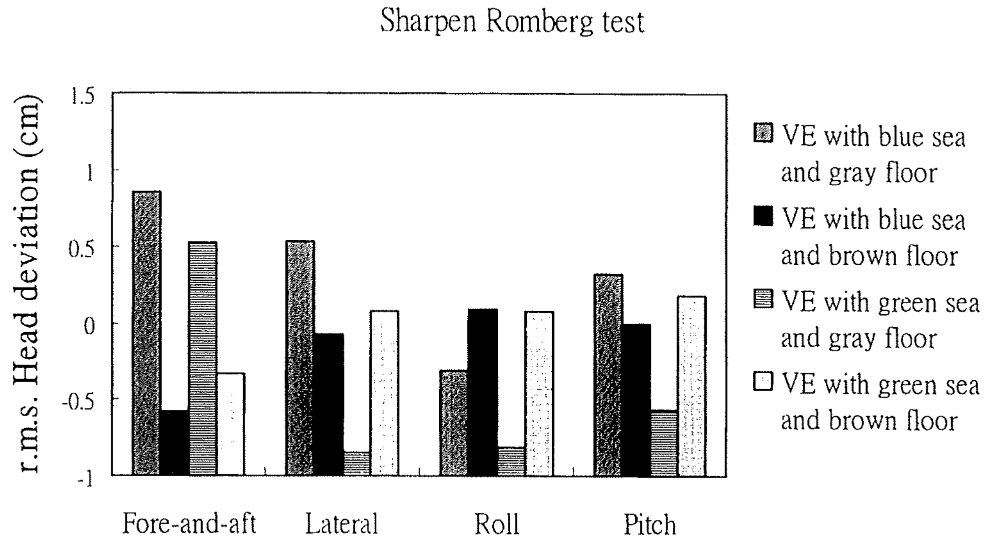


Figure G.1 The root-mean-square (r.m.s.) head deviations in 4 directions (fore-and-aft, lateral, roll, pitch) during the Sharpened Romberg Test

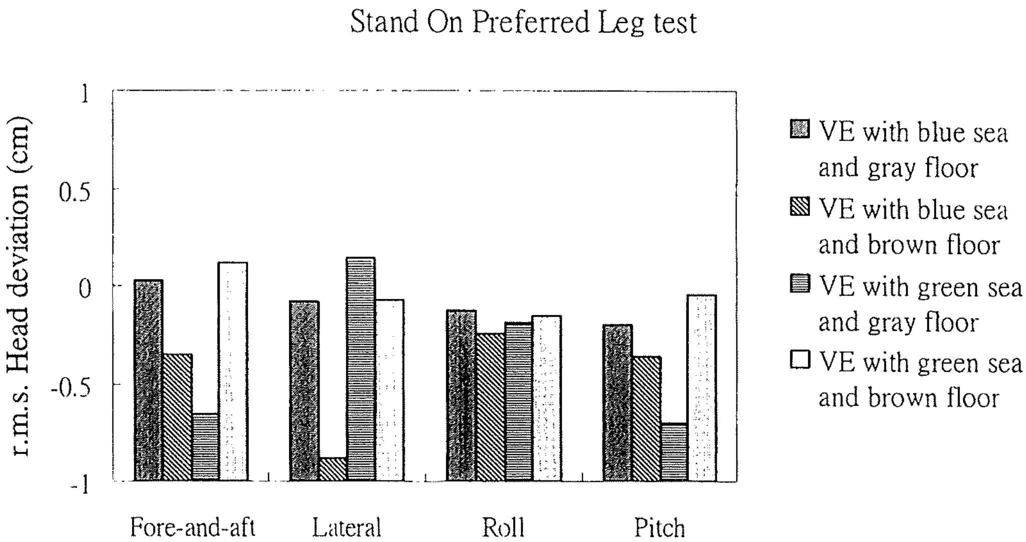


Figure G.2 The root-mean-square (r.m.s.) head deviations in 4 directions (fore-and-aft, lateral, roll, pitch) during the Stand On Preferred Leg Test

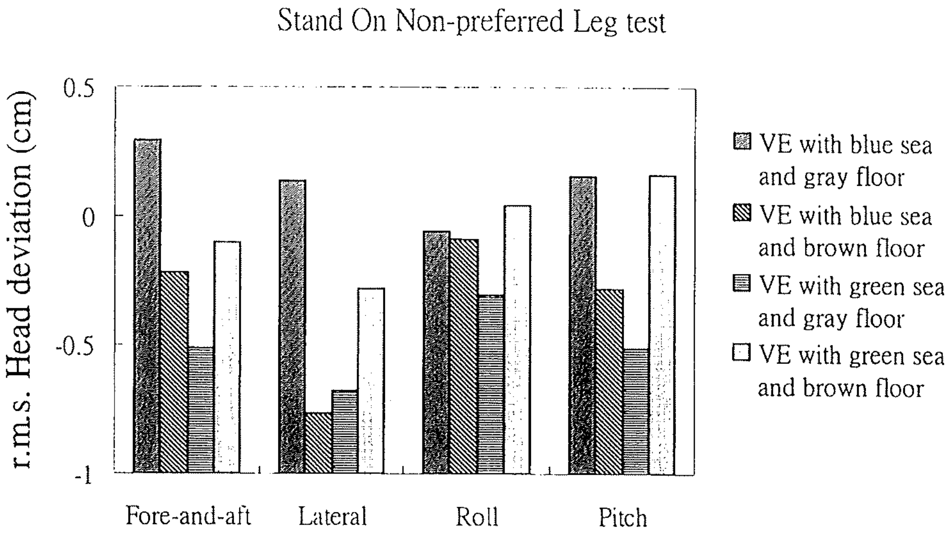


Figure G.3 The root-mean-square (r.m.s.) head deviations in 4 directions (fore-and-aft, lateral, roll, pitch) during the Stand On Non-preferred Leg Test

APPENDIX H Range of average radial spatial frequencies studied

The range of average radial spatial frequencies used in experiment 2 is from 0.002cpd to 0.413cpd. To consider whether this range is large enough, the highest possible radial spatial frequency is calculated. For a snapshot with a high spatial frequency, there should be more changes in luminance level and greater change in luminance level.

Consider the case of using a VR4 head-mounted display which was used in the experiments. It has a resolution of 495 pixels × 115 pixels: the highest radial spatial frequency it can present would be a picture of checkerboard, having alternating pixels change from pure write to pure black or vice versa (Figure H.1). The corresponding radial spatial frequency is 5.406cpds.

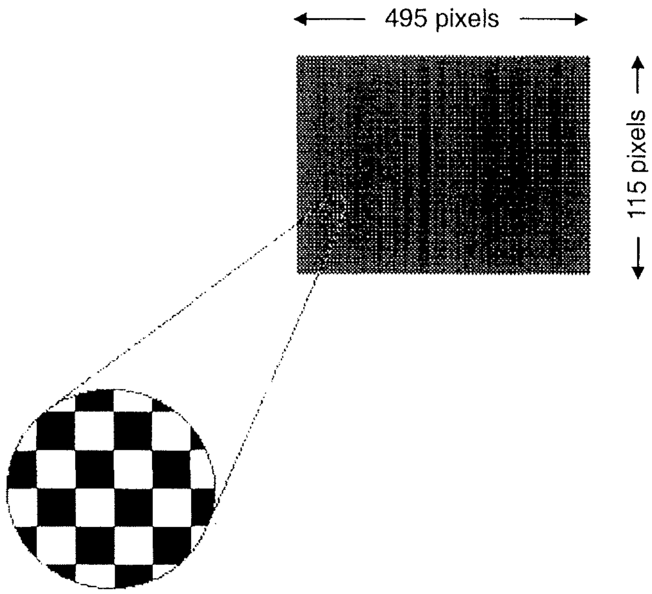


Figure H.1: Checkerboard-like picture shown with the resolution of VR4 HMD

In the case of a typical virtual environment, it is not quite possible to have such a high spatial frequency, especially in an outdoor virtual environment. This is because for an outdoor environment, a large portion of it is covered by the sky, which has few changes-and these are minimal.. (The sky and cloud were light in color during good weather and dark during bad weather). Similarly, the ground usually changed little from area to area. Hence, for a typical outdoor virtual environment, the average radial spatial frequency would be much lower than 5.406cpds.

Figure H.2 shows the average radial spatial frequency with ±2 standard deviation of the 5 sea-front virtual environments used in experiment 2. For the virtual environments with highest average radial spatial frequency, i.e. VE5 with 0.413cpd, snapshots at 2 standard deviations above the average is around 0.62cpd. It is still far from the highest possible radial spatial frequency 5.406cpd. Figure H.3 shows a snapshot of radial spatial frequency 0.611cpd. It is observable that the snapshot already contains a sky with many objects and a floor of complex texture. It is probable that most of the virtual environments would have a lower average radial spatial frequency than VE5. Hence, the range of average radial spatial frequency used for experiment 2 is quite reasonable.

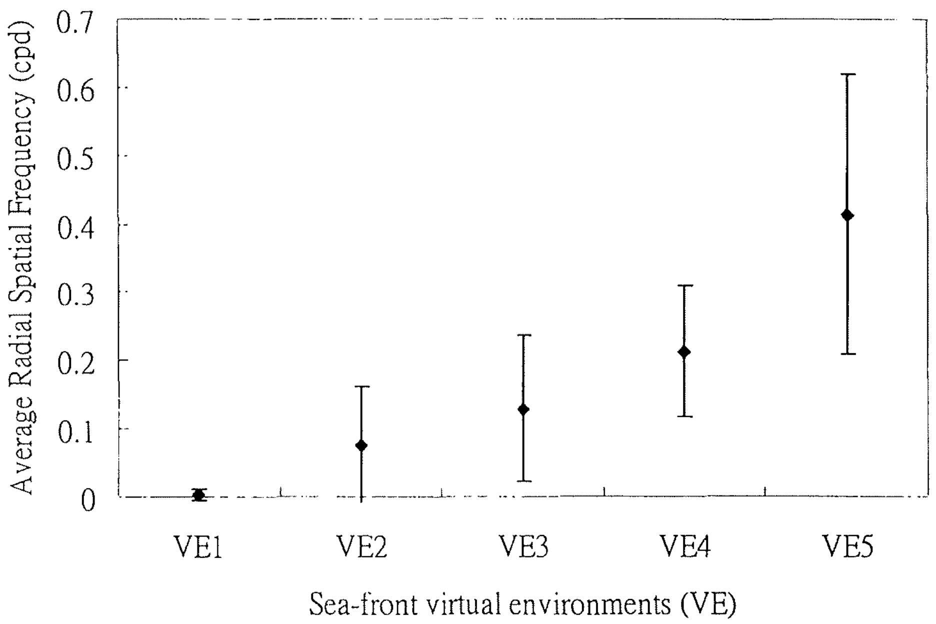


Figure H.2 The average radial spatial frequency of the 5 sea-front virtual environments used in experiment 2 (Mean with ±2 standard deviations).

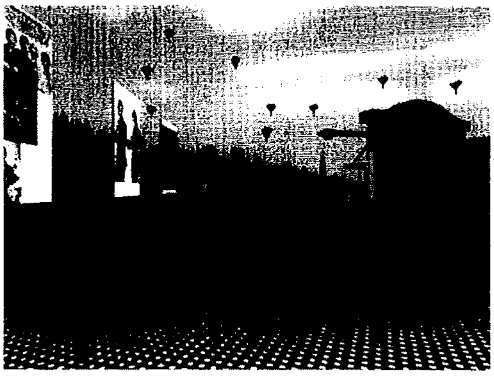


Figure H.3 A sample snapshots from VE5. The corresponding radial spatial frequency is 0.611cpd

However, it should be noted that the range might not be applicable to other types of virtual environments. E.g. for an indoor virtual environment, the ceiling, walls and floor could be of any texture. Therefore, it is possible for a room to have a lot of high spatial frequency mapping for the surroundings. Its average radial spatial frequency may much higher than that of a normal outdoor virtual environment.

APPENDIX I Results of postural for experiment 2 (Effects of spatial frequency on levels of cybersickness)

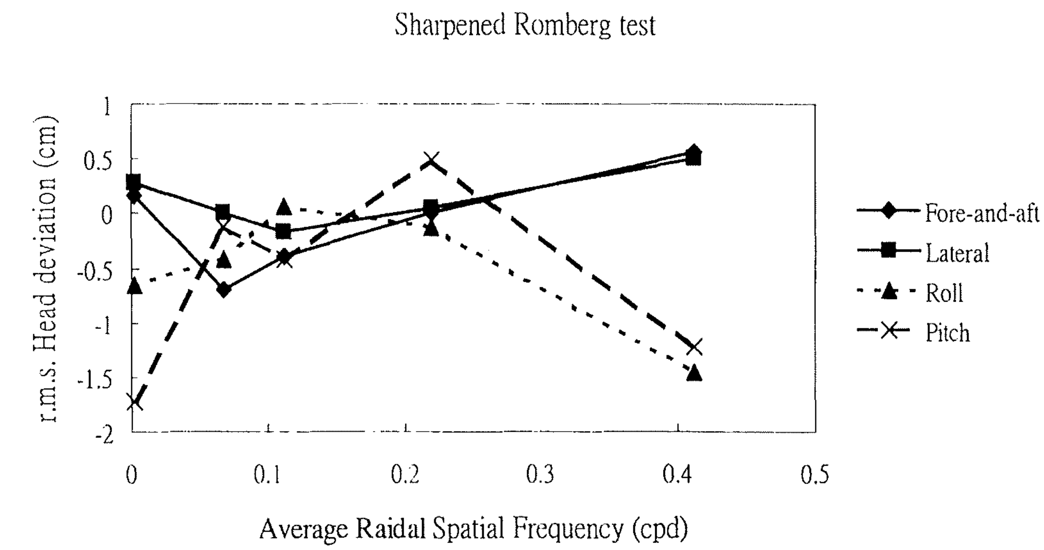


Figure I.1 The root-mean-square (r.m.s.) head deviations in 4 directions (fore-and-aft, lateral, roll, pitch) during the Sharpened Romberg Test

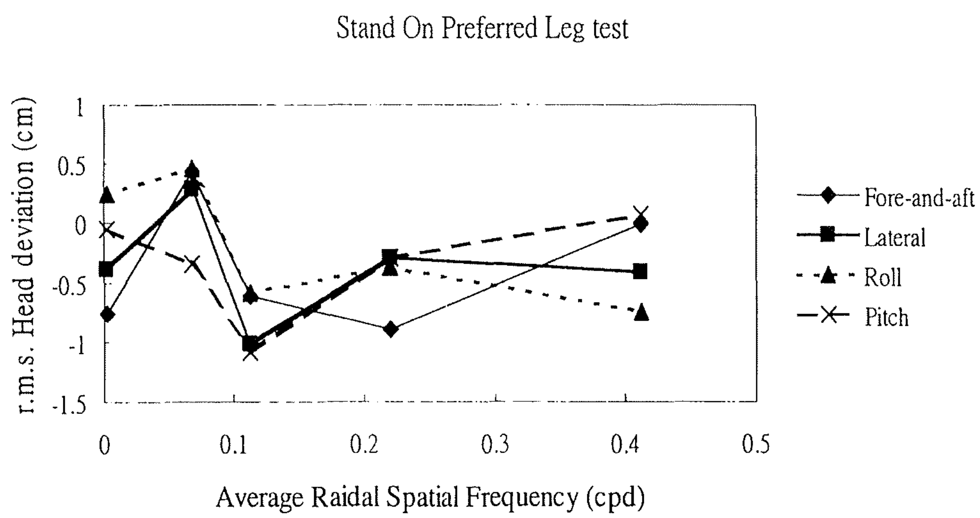


Figure I.2 The root-mean-square (r.m.s.) head deviations in 4 directions (fore-and-aft, lateral, roll, pitch) during the Stand On Preferred Leg Test

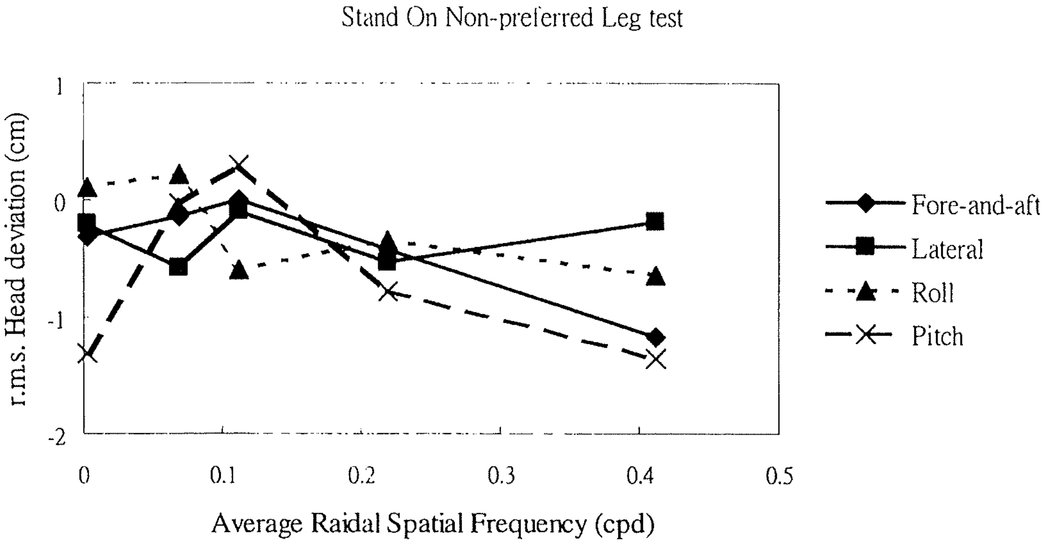


Figure I.3 The root-mean-square (r.m.s.) head deviations in 4 directions (fore-and-aft, lateral, roll, pitch) during the Stand On Non-preferred Leg Test

Appendix J Experimental Instruction for Experiment 1

Instruction to subjects - Experiment on the effects of color on cybersickness

1. You would be asked to read color blindness testing sheet and a color text.

2. You would be asked to complete the subject consent form, a pre-exposure symptom checklist. Read an instruction on postural test and the 7-point nausea ratings and the apparent self-motion ratings definitions.

7-point nausea ratings

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

4-point apparent self-motion ratings

Ratings	Definition
0	No
1	Slight
2	Moderate
3	Strong

3. The experimenter will measure your inter-pupillary distance (distance between 2 eyes).

4. Perform the pre-exposure postural test.

5. One minutes practice to familiarizes with the VR system.

6. 40 minutes duration in the VR environment.

   During the experiment, at each 30 seconds interval, the experimenter will ask you turn your head to right or left. The experimenter will ask you "What do you see?" please answer the question in shortly, e.g. " A building", and then turn your head back to the front again.

   During the same experiment, between five minutes interval, the experimenter will obtain verbally a nausea rating and apparent self-motion rating from you.

7. Complete the post symptom checklist and perform post-exposure postural test.

8. Get paid for $50/hr and sign your name in the sheet provided by the experiment.

9. Now do you have any question?

Appendix K Experimental Instruction for Experiment 2

Instruction to subjects - Experiment on the effects of spatial frequency on cybersickness

1. You would be asked to read color blindness testing sheet and a color text.

2. You would be asked to complete the subject consent form, a pre-exposure symptom checklist. Read an instruction on postural test and the 7-point nausea ratings and the apparent self-motion ratings definitions.

7-point nausea ratings

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

4-point apparent self-motion ratings

Ratings	Definition
0	No
1	Slight
2	Moderate
3	Strong

3. The experimenter will measure your inter-pupillary distance (distance between 2 eyes).

4. Perform the pre-exposure postural test.

5. One minutes practice to familiarizes with the VR system.

6. 30 minutes duration in the VR environment.

   During the experiment, at each 30 seconds interval, the experimenter will ask you turn your head to right or left. The experimenter will ask you "What do you see?" please answer the question in shortly, e.g. " A building", and then turn your head back to the front again.
   During the same experiment, between five minutes interval, the experimenter will obtain verbally a nausea rating and apparent self-motion rating from you.

7. Complete the post symptom checklist and perform post-exposure postural test.

8. Get paid for $50/hr and sign your name in the sheet provided by the experiment.

9. Now do you have any question?

Appendix L Experiment Instruction for postural test

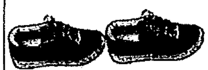
Instructions to subjects - Postural Test (Static Test)

1. You would perform this postural test before and after the virtual environment exposure

2. You have to wear flat, hard-soled shoes.

3. You would be asked to stand on one leg. (For leg preference)

4. You would perform three postural tests. Details of the tests are as follow:

Test Name	Sharpened Romberg (SR)	Stand-on-Preferred-Leg (SOPL)	Stand-on-Non-preferred-Leg (SONL)
Posture	Stand Heel-to-Toe 	Stand on Preferred Leg, other leg bent at knee	Stand on Non-preferred Leg, other leg bent at knee
	Arms folded across chest		
	Eyes closed		
Duration	Max: 60s	Max: 30s	Max: 30s
False start	Less than 5s	Less than 5s	Less than 5s

5. Experimenter would demonstrate all the postural tests.

6. Sequence of the tests is as follow:
   - 4 trials of SR Test
   - 3 trials for both SOPL and SONL tests, alternating order

   There will be a 30s rest after each trial

Appendix M Pre-exposure Simulator Sickness Questionnaire

SYMPTOM CHECKLIST (Pre-exposure)

Confidential

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

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

Appendix N Post-exposure Simulator Sickness Questionnaire

SYMPTOM CHECKLIST (Post-exposure)

Confidential

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

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