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Study on Simulator Sickness in Immersive Virtual Environment and Proposal for Safety Guidelines

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Abstract

Immersive virtual environment (IVE) definitions in this research are 1) multiple large flat-screened, 2) can accommodate more than one user at the same time, and 3) different types of user as "driver" and "passenger". Therefore, head-mounted display (HMD), Concave screen, one large projection screen and a monitor screen are not IVE from these definitions. CAVE Automatic Virtual Environment (CAVE) is one type of IVE. The current CAVE used by only one user at one time. However, the CAVE screen size is increasing in coming future. The larger CAVE can support more than one user simultaneously enter at the same time while these users see the screen from different positions ("driver" versus "passenger"). The previous published papers were less studying on simulator sickness in CAVE system. Furthermore, driver and passenger positions effect on simulator sickness in IVE have not been published. Therefore, this research purpose is proposing the safety guidelines which reduces the simulator sickness in an immersive virtual environment by study multiple factors of simulator sickness in an immersive virtual environment, and investigated their order of importance from factor loadings through subject experiments based on a Simulator Sickness Questionnaire (SSQ). To better determine the factors of simulator sickness in multiple-screened IVE, this research studied both environmental factor effects on simulator sickness such as position, parallax, and number of display screens, and also subject factor effects such as age and height differences. The HoloStage™ experiment with various environmental conditions then evaluated by Motion Sickness History Questionnaire (MSHQ) and a follow-up simulator sickness questionnaire. In addition, the physiological measurement of heartbeat rate from ECG was analyzed in the last experiment of this research.

Experiment 1 is the study of display screen and parallax effects. Experimental results show three-screened induced simulator sickness less than one-screened when comparing in simulator sickness questionnaire total score. However, the oculomotor is affected on simulator sickness from three-screened more than one-screened when parallax is 2.0 cm. This experiment results suggest to use three-screened IVE while pay attentional set proper parameter conditions.

Experiment 2 is the study of parallax, position, height difference, nationality, and age effects by using wide-road content. The most factor effects of simulator sickness in descending order as parallax, position, height difference, nationality and age. However, the wide-road content is not obvious shown image distortion to the passenger. Therefore, Experiment 3 is the study of position effect by using narrow-road content. Position, height difference, and age effect on simulator sickness are studied in this experiment. The most factor effects of simulator sickness in descending order as position, height difference and age. Finally, experiment 4 is the study of the important factor effect and their order. The results show the most factor effects of simulator sickness in descending order as parallax, position and height difference effects. Moreover, the relationship between SSQ and heartbeat rate results was investigated in this experiment.

Regarding to the findings in these studies, three-screened displays produce less simulator sickness than one-screened displays but need attention to set proper parameters, e.g. should set parallax to 6.5 cm. Moreover, the simulator sickness can be reduced in multiple-screened immersive virtual environments by setting the tallest subject as the driver, and having the passenger avoid the position where the screens connect together. Furthermore, the safety guidelines for experiment in immersive virtual environment and safety guidelines for IVE are proposed.

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Chompoonuch Jinjakam

Tokai University

To

My parents,

grandmother,

and daughter

Chapter 1

Introduction

1.1 Background

Immersive virtual environment (IVE) becomes currently considerable and omnipresent technology in several fields as entertainment purpose, training, medicine, architecture and Telepresence.

This research study defines the immersive virtual environment as: 1) two or more display flat-screened which are larger than the subject's height (the flat one-screened and flat three-screened will be called 'one-screened' and 'three-screened' in this research). With this size of screen, the subject's awareness of the physical self is diminished or lost by being surrounded in an engrossing total virtual environment. 2) more than one subject can accommodate at the same time, and 3) there are two different types of subjects, as 'driver' and 'passenger' positions.

In the past fourteen years, research regarding simulator sickness and virtual reality has focused primarily on non-immersive virtual reality with one large projection screen and a curved projection screen [1]-[5], real image and virtual image [6], and only a few research papers in IVE, especially in CAVE automatic virtual environment (CAVE), have been published.

Although the head-mounted display (HMD) and CAVE are both immersive virtual environments, there is an important difference between them. Regarding HMD, even though HMD glasses can be worn by more than one person at a time, each pair of glasses offers its own IVE display and each user's viewpoint is not affected by the other. While using CAVE, however, simultaneous users see the same IVE display, each from his own position. In this study, the terms "driver" and "passenger" are used to describe simultaneous users and their positions. The "driver" is a subject who wears the control glasses, and the scene viewpoint synchronizes and is changed depending upon his head movement. The "passenger" is a subject who only sees the three-dimensional scene, but his head movement does not affect the scenic viewpoint. Details regarding driver and passenger positions which may affect simulator sickness will be described further later. Only a small amount of previous research [7] has been conducted regarding the effect of the difference between driver and passenger positions in immersive virtual environments. There also have not been any official published guidelines for a safe virtual display in IVE. Although one large screen can accommodate more than one subject at a time, but views are the same looking through similar stereo glasses. The use of one large screen is different than that used in the CAVE and not studied for position effect.

Several factors associated with simulator sickness in virtual environments have been proposed as shaky-stabilized image [8], color break up [8], content effect [5] [9], peripheral vision and motion parallax [10], real walking effect [11], pre/post-test questionnaire [12] [13], navigation style and display size [14], dynamic virtual reality environment [15], field of view [16] [17], gender [18], age [19], habituation [20], rotational scene oscillations [21] [22], stressful task [23], and previous experience with simulator [24]. The symptoms on simulator sickness have been published as fatigue [3] [8], vision factor [3], arousal factor [3], mental and spatial rotation [18], balance [17], nausea [25], and symptom in the simulator sickness questionnaire (SSQ).

1.2 Purpose of research

The purpose of this research is to propose the safety guidelines which reduce the simulator sickness in an immersive virtual environment by studying multiple factors on simulator sickness in an immersive virtual environment, and investigation of their factor loadings through subject experiments based on a simulator sickness questionnaire. The heart beat is also comparative study with simulator sickness questionnaire results.

Although this new technology is widely used, but some users indicate simulator sickness symptom from the virtual environment. Simulator sickness is a significant problem for a number of individuals who use virtual environments. Simulator sickness is difficult to predict because there are so many factors that can contribute to its cause both from technological and individual standpoints [1]. The environmental and human factors which may affect simulator sickness are studied in this research. The environmental factors were composed of parallax, number of display screens and subject position, while the human factors were age, height difference between a driver/passenger and nationality. In this study, the purposefully designed of immersive virtual environment for each experiment and evaluated the subject after the experiment by using a simulator sickness questionnaire. Furthermore, based on data collected in this study, the methods of displaying an IVE to reduce simulator sickness are proposed.

1.3 Previous literature review of simulator sickness experiments

Thirty-four research papers related to simulator sickness in virtual environments published from 1999 to 2012 [3-6] [8-13] [15-16] [18] [20-23] [25-41] are reviewed. Table 1.1 shows the number of reviewing papers divided by virtual environment display type, number of subjects in the experiment, duration of the experiment, and simulator sickness measurement methods.

The most previous research has focused on simulator sickness in virtual environments with subject numbers ranging from 11 to 20 people, as shown in Table 1.1. This research also follow with subject groups in this population range. Larger subject groups in previous research were recruited students. For instance, 53 subjects [23] were recruited from a college population, 128 subjects [40] were undergraduate students who received a research credit for participating, and 200 subjects [41] were taking part in an IVE course.

Most of the published research included experiments lasting 3-6 minutes (13 papers) and only one paper was based on an 8-minute experiment. Therefore, the duration of the experiments in this study was also 3-6 minutes. Previous research with longer experiment times involved a driving simulator (60 minutes) in a long-term simulator sickness study [26], and 1-1.5 hours for the effects of field-of-view (FOV) on the presence, enjoyment, and memory [16].

Table 1.1 Review papers on simulator sickness in virtual reality from year 1999 - 2012.

Equipment	No. of papers	No. of subjects	No. of papers	Duration of experiment (min)	No. of papers	Measurement method	No. of papers
						• *Quantitative measurement*	
Desktop/TV monitor	4	1- 10	6	3 - 8	14	ECG	12
Projection screen	19	11- 20	11	10-20	9	EEG	5
HMD	11	21- 30	7	30-40	2	Skin response	4
CAVE	5	31- 40	3	60 up	3	Body sway	3
		41-200	7	Task assigned	6	PPG	3
						EOG	2
						• *Questionnaire/ self-report*	
Note: Five papers compare more than two equipment types.						SSQ	19
						MSHQ	4
						Anxiety scale	1
						Malaise rating	1
						Manikin&presence	1
						STAI	1

Abbreviation : Electrocardiogram (ECG), Electroencephalogram (EEG), Fingertip Photoplethysmogram (PPG), Electroculogram (EOG), Simulator Sickness Questionnaire (SSQ), Motion Sickness History Questionnaire (MSHQ), Spielberger State-Trait Inventory (STAI)

Measurement methods for ascertaining the amount on simulator sickness can be divided into two types: self-report and the collection of quantitative data. This study used the most common self-report method which is known as the simulator sickness questionnaire and used the electrocardiogram (ECG) to gather quantitative data in heart beat per minute (BPM).

Table 1.2 CAVE research from year 2007 to 2012.

	CAVE [42]	CAVE [30]	CAVE [9]	CAVE [37]	CAVE [23]	This Research
Year	2007	2007	2008	2008	2012	2012
No. of subject	10	21	18	20	53	33
Gender	9M, 1F	9M, 13F	N/A	N/A	N/A	27M, 6F
Duration (min.)	14	16	10	4	Task assigned	5
Difference driver vs. passenger	×	×	×	×	×	○
Reason of sickness	Visual-vestibular conflict produced by VR	Accelerati on around the yaw and pitch axes in VR	Viewing stimulus around the yaw axis, zoom, and up-and-down linear acceleration	Psychotic symptom of paranoia	Low and high-stress tasks in Desktop, HMD, and CAVE	Driver-passenger position, height difference, parallax, age
Evaluation methods	HRV	HRV	SSQ, HRV	SSQ	SSQ	SSQ, BPM

Abbreviation : Heart Rate Variability (HRV), Simulator Sickness Questionnaire (SSQ), Heart Beat Per Minute (BPM)

The published papers in simulator sickness in CAVE research from year 2007 to 2012 are only 5 papers. Table 1.2 shows none of the previous CAVE research are studied the difference between driver and passenger position effect. Moreover, each research was studied only one factor effect or comparing the difference between different IVE devices. Therefore, this research study multiple factors in parallax, driver and passenger positions, height difference, and age effect, then order the importance of each factor effect to simulator sickness. Finally, the safety guideline for IVE is proposed.

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Chapter 2

3D Environment

2.1 Virtual reality definition

Virtual reality (VR) is a high-end user-computer interface that involves real-time simulation and interactions through multiple sensorial channels. These sensorial modalities are visual, auditory, tactile, smell, and taste [1].

The virtual environment system consists of a human operator, a human-machine interface, and a computer. The computer and the displays and controls in the interface are configured to immerse the operator in an environment containing three-dimensional objects with three-dimensional locations and orientations in three-dimensional space. Each virtual object has a location and orientation in the surrounding space that is independent of the operator's viewpoint, and the operator can interact with these objects in real time using a variety of motor output channels to manipulate them [2].

VR systems most configurations into three main categories [3] and each category can be ranked by the sense of immersion or degree of presence.

- Non-Immersive (Desktop) Systems: by utilized a standard high resolution monitor and 3D interaction devices as DataGlove.

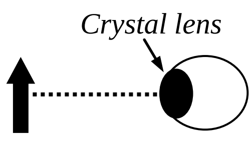
- Semi-Immersive Projection System: comprise of a relatively high performance graphic computing system with a large screen monitor or large screen projector system, similar to IMAX theatres.
    - Liquid Crystal Shutter (LCS) glasses.
- Fully Immersive Display Systems
    - Head Mounted Displays (HMDs)
    - CAVE, HoloStage™

2.2 3D displays

2.2.1 Principle of stereoscopic vision [4]

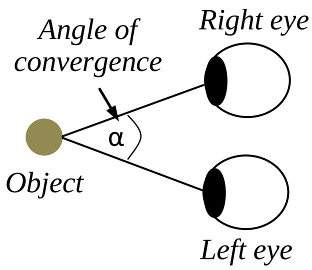
The three dimensions and cue depth as show in Fig. 2.1 are from

- Focal accommodation of crystal lens
- Convergence of both eyes
- Binocular disparity
    - The distance between the right and left eye is between 5-7 centimeters. Therefore, the different viewpoints makes recognize different images.
- Monocular movement parallax
- Size of objects
- Height of objects
- Overlapping of objects
- Density of texture
- Shape
- Lighting
- Contrast
- Saturation
- Hue, and
- Definition

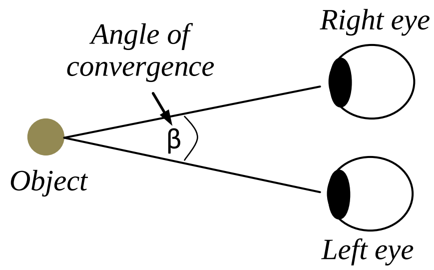


(a) Crystal lens become thicker when objects closed to eye

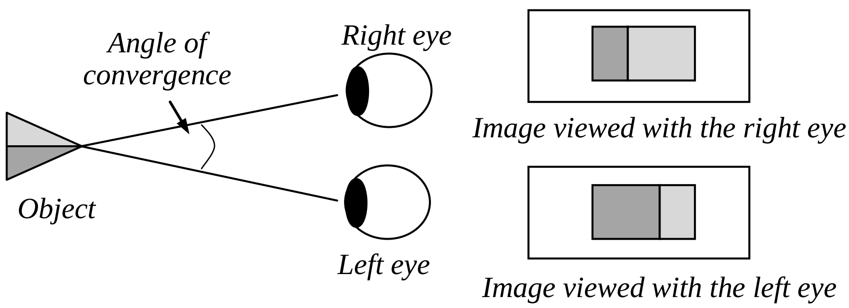
(b) Crystal lens become thinner when objects far from eye



(c) Angle of convergence becomes larger when objects close to eye or $\alpha > \beta$



(d) Angle of convergence becomes smaller when objects far from eye or $\alpha < \beta$



(e) Binocular disparity; the different viewpoint makes eye recognize different images

Figure 2.1 Depth cues properties.

2.2.2 Mechanism of 3D displays based on binocular disparity principle [3]

The distance between left and right eye is around 5-7 centimeters. Therefore, images which are recognized with each eye differ due to differences of their viewpoints. The closer the distance to the subject is the bigger the difference becomes, and vice versa. The human brain recognizes three dimensions according to the difference. Consequently, separately providing images with different viewpoints to the right and the left eye makes the depth feeling, as shown in Fig. 2.2. 3D displays utilize binocular disparity and provide different images on right and left eye by using methods such as barriers. For example, if images for the right eye and the left eye are allocated on the display based on this principle as in the illustration below, we can recognize a three dimensional box extruded from the surface of the display.

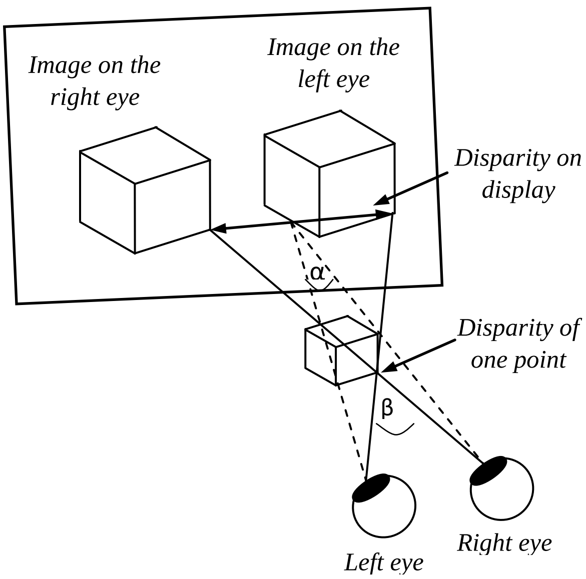


Figure 2.2 Three dimension display.

2.3 Immersive virtual environment

2.3.1 CAVE Automatic Virtual Environment [1]

CAVE is the type of projector-based display, which was invented at the Electronic Visualization Laboratory of the University of Illinois at Chicago. It consists of four CRT projectors, on each for the front, the left and right sides, and the floor. Each projector is driven by different graphics pipeline signals received from a four-pipe computer. Three projectors are retro projection, with the projectors placed on the surrounding floor and reflecting the image off mirrors. The image shown on the floor display is produced by a projector placed on top of the CAVE, and is reflected downward by a mirror assembly. Users wearing active glasses see a very convincing 3D scene, including objects that seem to grow upward from the floor. The size of the CAVE up to 12 users at a time, as long as they stay still or move together. Commercial version of the CAVE includes the Immersive WorkRoom (4.0 m wide × 10.7 m deep × 7.6 m high) from Fakespace Systems and the smaller ReActor (3.0 m wide × 2.9 m deep × 2.8 m high) from Trimension Systems Ltd. A newer version called RAVE (for "reconfigurable virtual environment") offers additional flexibility since it is constructed of four modules. Each 3.0 m wide × 2.9 m deep × 3.7 m high module has its own screen and projector assembly. This gives users the added flexibility of changing the viewing configuration from a cube, to two L-shaped displays, to a wall-like configuration, based on application-specific needs.

CAVE's costs (excluding the high-end multiple graphics workstation) is about $300,000, while the RAVE costs about $500,000. It is therefore not surprising that various research groups around the world are working on less expensive CAVE variants, and also the research in this system of immersive virtual environment is less when compared with the other virtual environment equipment.

2.3.2 HoloStage™

Tokai University uses a three-screened HoloStage™ system which is an immersive virtual environment used for educational and research purposes. The HoloStage™ system is a CAVE virtual reality environment using the HP Z800 Workstation HoloStage ® Christie Digital Systems, Japan [5]. Screens (5.4m × 3.0 m × 3.0m) are placed in the front, on the right, and on the floor with a wide viewing angle of the projector to five solid Mirage 3D with high-resolution high-brightness (Lumens brightness and 6600ANSI, 10 with the Mirage WU7 with a resolution WUXGA) projectors as shown in Figure 2.3. Thus, the combination of screens is large enough to accommodate a group of users who can all be in the immersive virtual environment simultaneously. Experiment 2, 3 and 4 were tested with this HoloStage™ system at the Takanawa campus. The HoloStage™ system is shown in Fig. 2.4 (a). However, experiment 1 was conducted using a HoloStage™ system which used three screens (4.0m × 2.0m × 2.0m) at the Shonan campus but that is no longer in use.

There were two types of glasses in the experiment: glasses for driver (Fig. 2.4 (b)) and glasses for passenger (Fig. 2.4 (c)) that are called control glasses and stereo glasses later in this thesis.

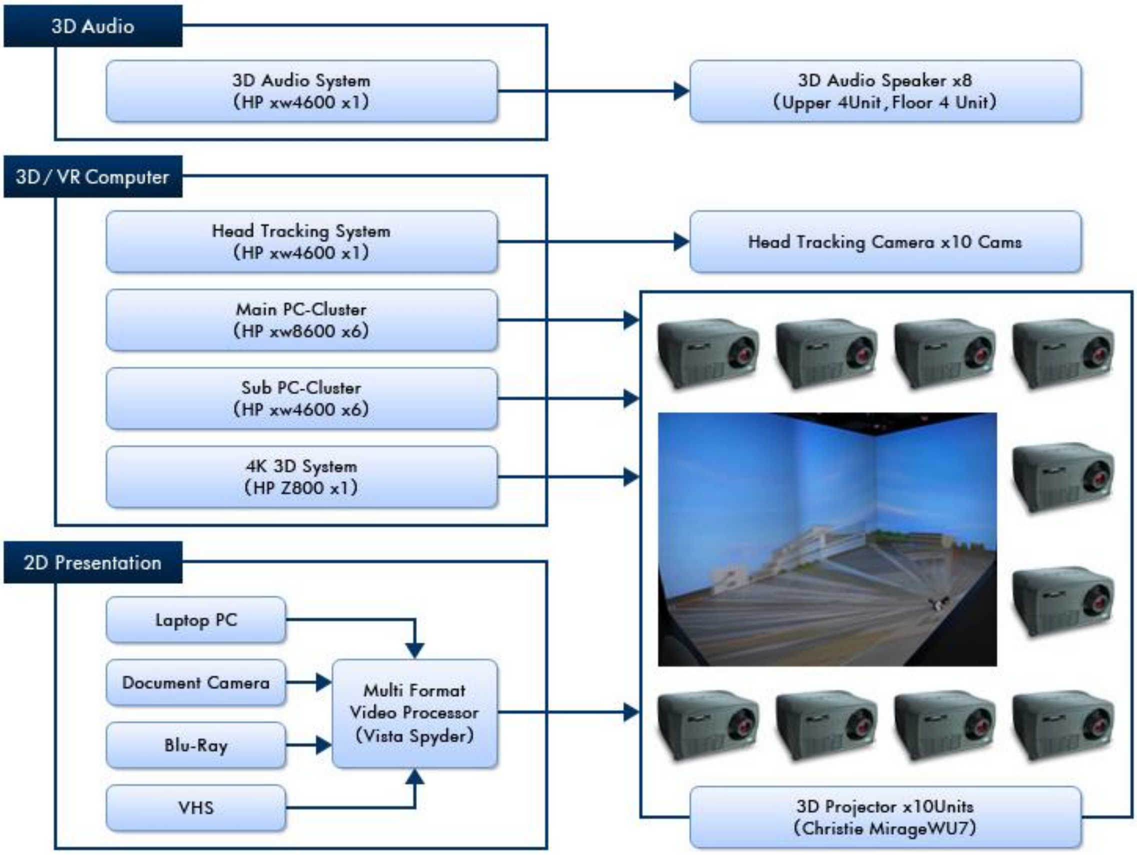


Figure 2.3 Diagram of HoloStage™ [5] at Tokai University, Takanawa Campus.

(a)

(b)

(c)

Figure 2.4 (a) HoloStage™ at Tokai University, Takanawa campus.

(b) glasses for driver (c) glasses for passenger.

The control glasses sent signals to receivers in the HoloStage™ system indicating how the driver moved his head. Then the HoloStage™ system made synchronized changes according to the virtual scene viewpoint. Thus, the virtual scene was completely adjusted to the driver. The passenger could see three-dimensional scenes but his head movement was not affected by the virtual scene viewpoint. Therefore, the driver always sees the natural virtual scene while the passenger does not. Because passenger has to see the driver's view from different viewpoints. Therefore, the passenger's scene is distorted, especially on border connection. The position effect between driver and passenger is studied in this research.

In terms of the virtual scenery content, a general view was chosen for each experiment that would be seen in everyday life. It was composed of a walk-through road, house, bridge, space area and high building all in common colors. All buildings were fixed, but one car object moved. Also, no audio included in the virtual environment.

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Chapter 3

Evaluation methods of simulator sickness

The common methods [1] used for measuring presence are 1) subjective measures that rely on self-assessment by a user, 2) behavioral measures by examining actions or manner exhibited by a user that are responses to objects or events in the virtual environment, and 3) physiological measures by gauging changes in a subject's heart rate, skin temperature, skin conductance, breathing rate, etc.

The advantages of subjective measures are their face validity and the ease of use of questionnaires. These questionnaires also do not interfere with the user's experience while in the virtual environment, and also inexpensive. On the other hand, the disadvantage of post-immersion questionnaire is they are not measuring the time-varying qualities of presence.

Behavioral measures advantages are their shielded from subject bias, but the disadvantage is inability to know for a fact that a certain behavior was caused by the experimental condition.

Physiological measures advantages are more objective and continuous measure, then time-varying qualities can be observed. However, physiological levels vary widely from person to person so experiment must measure baseline level and produce results based on changes compared to that baseline rather than absolute value. Moreover, some physiological measure as skin temperature is slow to change, it takes up to five minutes to reach a peak skin temperature.

In this research, the simulator sickness questionnaire is used for subjective measurement and also the heart beat measure from electrocardiogram signal is used for physiological measurement. Nevertheless, the behavior measures are not used in this research study.

3.1 Simulator sickness questionnaire

The Simulator Sickness Questionnaire (SSQ) [2] is developed from the Pensacola Motion Sickness Questionnaire (MSQ) by cut irrelevant and misleading questions. The objective of SSQ is (a) to provide more valid index of overall simulator sickness severity as distinguished from motion sickness, (b) to provide subscale scores that are more diagnostic of the locus of simulator sickness in a particular simulator for which overall severity was shown to be a problem, and (c) to provide a scoring approach to make monitoring and cumulative tracking relatively straightforward.

From the purpose to determine which symptoms showed systematic changes from pre-exposure to post-exposure, symptoms selected too infrequently to be of value as statistical indicator and symptoms that showed no change in frequency or severity where eliminated from further analyses. Symptoms that might give misleading indications were also eliminated from subsequent analysis. Symptoms that might give misleading indications were also eliminated from subsequent analysis. These symptoms hand their highest frequency of occurrence in simulators that had little or no other indicated symptomatology, and were rarely seen in simulators that had high frequency or severity on most other symptoms. Altogether, 12 of 28 symptoms were eliminated, as identified in Table 3.1.

Table 3.1 Symptoms in MSQ and SSQ

MSQ Symptom	*Retained for SSQ*	*Eliminated for SSQ*
General discomfort	x	
Fatigue	x	
Boredom		x
Drowsiness		x
Headache	x	
Eyestrain	x	
Difficulty focusing	x	
Increased salivation	x	
Decreased salivation		x
Sweating	x	
Nausea	x	
Difficulty concentrating	x	
Depression		x
Fullness of head	x	
Blurred vision	x	
Dizzy (eyes open)	x	
Dizzy (eyes closed)	x	
Vertigo	x	
Visual flashbacks		x
Faintness		x
Awareness of breathing		x
Stomach awareness	x	
Decreased appetite		x
Increased appetite		x
Desire to move bowels		x
Confusion		x
Burping	x	
Vomiting		x

In order to use the SSQ, it is necessary to administer either a form containing the 16 symptoms indentified in Table 3.1 with the 4-point scale for all items. The information should be done after perform consent from all subjects and check the present states of their health. The scoring procedures presume that all individuals in other than their usual state of fitness are eliminated from the sample, and that only post-exposure data are scored.

Table 3.2 Computation of SSQ scores

	Weight		
SSQ Symptom[a]	*N*	*O*	*D*
General discomfort	1	1	
Fatigue		1	
Headache		1	
Eyestrain		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[b]	[1]	[2]	[3]

Score
N = [1] × 9.54
O = [2] × 7.58
D = [3] × 13.92
TS[c] = ([1] + [2] + [3]) × 3.74

[a]Scored 0, 1, 2, 3. [b]Sum obtained by adding symptom scores. Omitted scores are zero. [c]Total Score.

The analysis were conducted extracting three-factor solutions from the 16 symptom variables. The three distinct symptom clusters were labeled Oculomotor (O; eyestrain, difficulty focusing, blurred vision, headache), Disorientation (D; dizziness, vertigo), and Nausea (N; nausea, stomach awareness, increased salivation, burping). The three-factor solution suggested the existence of three (partially) independent symptom clusters, each reflecting the impact of simulator exposure on a different "target system" within the human.

Table 3.2 contains the scoring procedures for the SSQ. The SSQ uses unit weights and is both simpler to use and more stable than scoring based on more precise weights defined by varimax factor weights. To compute the scale scores, each symptom variable score (0, 1, 2, 3) was multiplied by the appropriate weight, and the weighted values were summed down the column to obtain the total weight.

The N, O, and D scores are then calculated from the weighted totals using the conversion formulas given at the bottom of the table 3.2. The total score (TS) is obtained by summing all the weighted totals and applying the TS conversion formula.

In experiment 1-4, the SSQ was measured only post- experiment because reports of simulator sickness after immersion in a virtual environment have been known to be inflated when both pre- and post- questionnaires are given compared to when only a post-test questionnaire is used [3].

3.2 Heartbeat rate measurement

Heartbeat rate is calculated in beat per minute (BPM) from ECG signal. Subject's heartbeat rate vary considerably, depend on their activity, level of fitness, medications, and age. Normal resting heart rate can be between 60 and 100 beats per minute in human aged 18 or more years. The healthier person usually has lower heart rate.

According to the National Health Service, UK [6], the following are ideal normal pulse rates at rest, in bpm (beats per minute):

- Newborn baby - 120 to 160
- Baby aged from 1 to 12 months - 80 to 140
- Baby/toddler aged from 1 to 2 years - 80 to 130
- Toddler/young child aged 2 to 6 years - 75 to 120
- Child aged 7 to 12 years - 75 to 110
- Adult aged 18+ years - 60 to 100
- Adult athlete - 40 to 60

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Chapter 4

Proposal for guidelines for experiment in immersive virtual environment

Virtual reality is widely used in many fields but still some subjects suffer from simulator sickness. Therefore, the simulator sickness from virtual environment (VE) are intensively continued study in these two decades to find and reduce the reason of sickness. The most widely accepted theory is that mismatches (due to system design issues or technological deficiencies) between the sensory stimulation provided by a simulator and the stimulation expected due to real-world experiences are the primary cause of motion sickness [1]. There are amount of research publications in a virtual environment that are studies on simulator sickness effect in various purposes, devices, experiment scene contents, target groups and measurement methods are studied and then report for simulator sickness effect. The appropriate preparing beforehand to experiment is suggested. Chapter 4 proposes the guideline for immersive virtual environment experiments [2] by describing the preparation for the subjects and equipments prior to experiment, and condition for the experiment. Furthermore, the virtual environment factors that related to simulator sickness based on survey previous researches and literatures are briefly shown in this chapter.

4.1 Simulator sickness related factor

4.1.1 Gender effect

Gender effects were observed in the virtual environment in term of task demands and motor involvement. Gender differences were also seen in the patterns of correlations between rotation tasks and other neuropsychological measures. Moreover, research results suggest male may rely more on left hemisphere processing than female when engaged in rotational tasks and female's rotation scores correlated mainly with spatial measures, while male's rotation scores correlated with both spatial and verbal measures [3]. This research results male can do logic task as rotation blocks task better than female then has a less simulator sickness.

The research paper [4] found a gender-difficulty interaction where male performed worse and responded slower to the attention task when the spatial task was more difficult, but no differences were observed for female between difficulty levels. Furthermore, the research suggests that the results may be pertinent to the design of virtual environment, then the nature and goal of the virtual environment tasks should be carefully considered to determine whether similar effects on performance can be expected under different conditions.

4.1.2 Age effect

The older subjects have more difficulty with simulator sickness or prone to have simulator sickness easier than younger adult subjects [5, 6]. One possible explanation is they are increased number of balance and dizziness problems experienced with aging. Our observation is the younger generation more familiar with simulation from movies or games than the older one, then more consequent practicing and experience in virtual reality.

4.1.3 Field of View (FOV)

With increasing FOV, subjects exhibited more dispersion and reported more difficulty keeping their balance and different scenes had different effects on postural stability [7]. Moreover, with increasing FOV, subjects reported more simulator sickness as well as increased E^2I score [8], when E^2I scale was developed to assess "engagement, enjoyment, and immersion" experienced by subjects in a VE. Similar with [9] high FOV reported higher feelings of presence than those in the low FOV conditions and higher levels of nausea.

Wide FOV displays allow more immersion in the virtual environment which may enhance the experience of 'presence'. On the other hand, stronger vection, this is one of the factors that may contribute to simulator sickness.

4.1.4 One-screened and three-screened

The body sway become larger when the stimuli were displayed on the three-screened as compared to only one-screened would seem to be that the far peripheral visual stimulation influenced the body sway which is affected by the sense of equilibrium. Hypothesized that the minimum sway was suppressed when the wide visual stimulation was displayed to the subject [10].

4.1.5 Simulation content

There are several types of contents in virtual environment as car drive simulation, walkthrough simulation, task assignment and so forth. One notice is the drivers feel more immersed and present than do passengers [11], when driver is a person who wearing head tracking device that can control the viewpoint of scene direction but the passenger cannot.

To measure the optokinetic parameter to predict susceptibility to simulator sickness, the striped patterns rotating were used [10, 12]

4.1.6 Mark point

Research [10] represents a difference between gravity and head with reason why the head movement was smaller than the center of gravity maybe reason is the subjects were asked to gaze at a mark presented in front of them. And it was found that the sways of a head position and the center of gravity increase when far peripheral vision is stimulated by optokinetic images and when stimulation with the motion parallax.

4.1.7 Real walking and walk-through

The research in virtual environment are tested both real walking and simulated walking in the real world and simulate condition. Evan et.al [13] indicates simulated walking is a better choice for reducing simulator sickness during tasks requiring a navigationally complex environment and a long amount of time. Correspondence with their report for measures of overall simulator sickness, disorientation, nausea, and oculomotor discomfort were all higher scores in the natural walking condition than either the simulated walking or real walking condition than either the simulated walking or real world conditions. And they suggest simulated walking is a better choice for reducing simulator sickness during task requiring a navigationally complex environment and a along amount of time.

4.1.8 Rotational scene

In the presence of scene oscillation, both nausea ratings and SSQ scores increased at significantly higher rates than with no oscillation, and individual participants exhibited different susceptibilities along different rotational axes in VR with no significant difference [14]

4.1.9 Navigation style

Navigation performance was better with navigation aid under the study with large projection display condition. Navigation time with map navigation aid is shorter than without navigation aid, and real navigation aid use shortest time. Moreover, large projector display resulting is users moving faster than desktop monitor. [15]

4.1.10 Visual complexity

The visual complexity of the Animate-Virtual Actor with different levels: flat, cartoon, or lifelike about the navigational capabilities of desert ants result no significant differences in simulator sickness between groups [16].

4.1.11 Pre-test and post-test questionnaire

Motion sickness after immersion in a virtual environment are much greater when both pre and post questionnaire are given than when only a post test questionnaire is used [9]. From one specific problem with both pre-test and post-test using is that seeing the list of symptoms beforehand may increase the user's sensitivity to those symptoms and cue the participant that motion sickness is commonly experienced. The user, seeing the SSQ prior to immersion in the virtual environment, may be more aware of physiological changes than he or she otherwise would. Additionally, upon receiving a post-test questionnaire, the user may remember that these symptoms were recorded on the pre questionnaire and may perceive that the "appropriate answer" is to report differences between pre- and post-measure [17].

4.2 Proposal for pre-tests preparation

- Subjects should healthy and have normal or corrected to normal vision and not consuming illicit drugs or caffeine 12 hours prior to the experiment [18].
- Discourage virtual reality used by subjects with cold, flu, binocular, anomalies, or susceptibility to migraines or photic seizures [19].
- Avoid too bright light or noise and maintain proper room/air temperature [20].
- Avoid the measurement right after the meal (suggest for 2 hours after the meal) [20].
- Subjects should have normal vestibular function [21] (which controls the sense of movement and balance [39]) and sleep enough.
- Subjects might have pre-test as motion sickness history questionnaire (MSHQ) or mental rotation test (MRT) [18] or pre-test SSQ.

- Motion sickness history questionnaire (MSHQ) is the questionnaire that asks about motion sickness in history (please see Appendix A) e.g. how often they get seasick, airsick, carsick. The MSHQ is suggested to use before experiment in moving contents (ship, airplane, car, roller coaster, walk-through, etc.)
- Mental rotation test (MRT) is the questionnaire to test the ability of rotating mental representation of two-dimensional and three-dimensional objects. The MRT is suggested to use in specific task to assign content testing, e.g. male tends to be slightly faster in mental rotation tasks than female.

- Do not let subjects see someone else getting sick, do not let them do the real thing similar within VE in the same day, get set before turning the VE on, suggest subjects not to move their head during the experiment and turn off the VE before getting out [22].
- Minimize initial exposure time for strong stimuli (10 minutes or less) [20].
- For ECG measurement, time to adjust the new environment and resting state is needed. Moreover, during the measurement time should maintain a comfortable sitting position, don't move or talk, don't close the eyes or fall asleep, and don't control the breathing intentionally [21].
- The researcher should have informed consent from all subjects before start the experiment.
- Inform users they can/should discontinue the simulation if they so wish [20].

4.3 Proposal for informed consent

Federal Regulations regarding the protection of human subjects require researchers to obtain informed consent from each subject, to provide certain information about content, including "a description of any reasonably foreseeable risks or discomforts to the subjects" (45 CFR 46). Before the study, researcher regarding the incidence of simulator sickness from the VR content to all subjects and describe that some risk of simulator sickness would be occurred, then who are prone to resemble a kind of motion sickness may exclude themselves from the study. In addition, subjects may withdraw anytime during the study when they feel severe sickness [5].

4.4 Proposal for content

The content is depending on what factor that wants to investigate. From the previous literature review, this research suggests to choose the content regarding to symptom to investigate as;

1) Nausea and others simulator sickness investigation

- **Driving simulate content**
  - This content has accelerated with turn's basis. It should have short time training (e.g. 2 min.) before the real experiment. The duration of experiment time should be short (e.g. 3 min. [21],[5]). In case of habitation study should have moderately duration time in consecutive days (e.g. 20 min. in 5 consecutive days [22]). Moreover, the long-term study takes long duration experiment time from 1-1.5 hour [8].
- **Navigation content**
  - This content consists of move forward and a lot of turns. The duration time experiment should be short (5 min. [13]). In the case of study in performance of navigation should take the moderate time (30 min. [15]).
- **Roller coaster content**
  - This content is consisted of severe accelerating and rotation, the experiment time should be short (5 min. [23] or 6 min. [18]). (Note: Real roller coaster has more effects, e.g. wind and gravity, but 3D scene has only scene effect. Therefore, these might be reason of longer duration time in roller coaster content than real one.)
- **Rotational Scene Oscillations content**
  - The rotation as pitch, yaw, and roll study should experiment with moderate time (20 min. [14]).

2) Balances investigation

- In order to test the body balance, the test body balance content should be used as varied by field of view [7], Equilibrium test (two conditions: eyes open, eyes closed; 60 second each) and VR walking test in 30, 60 and 90 min. [26].

3) Psychophysiological changes investigation

- The content should assign tasks for testing the psycho physiological, e.g. finding objects (10 trash cans) in 5 min. [27].

4) Optokinetic Stimulation investigation

- The content should increase the number of eyes movement, e.g. static and moved stripes pattern sinusoidal rolled with specified amplitude, sampling frequency about 9 Hz for 3 min. [10] and striped patterns rotating at 60 degrees per second for 30 min. [12].

5) Gender difference investigation

- The gender difference can be tested by assigning tasks, e.g. grasping and moving a sphere shaped for 5 min. [3] or varied task difficulty and task type [4].

4.5 Proposal for post-experiment

- Post-test should be measured immediately or within 5 min after the experiment.
- Introduce a time period immediately after VR exposure in which users are not suggested to perform high-risk activities (driving, piloting, biking, etc.) [19].
- If necessary, follow up with users to monitor prolonged aftereffects [19].
- Researcher may analysis the significant difference with the statistic methods, e.g. Student's *t* test or Analysis of Variance (ANOVA), or Principal Component Analysis (PCA).

4.5.1 Measurement methods

Miscellaneous measurement devices are used to analyze simulator sickness symptom from subjective measures by self-report questionnaire and physiological measurements.

4.5.1.1 Self report questionnaires

- Simulator Sickness Questionnaire (SSQ)
- Motion Sickness History Questionnaire (MSHQ)
- Presence Questionnaire (PQ)
- Immersion Tendency Questionnaire (ITQ)
- Flow Questionnaire (FQ)
- Questionnaire for User Interface Satisfaction (QUIS) [27], and
- Mental Rotations Test (MRT) [1].

4.5.1.2 Physiological measurements

- Electrocardiogram (ECG)
- Electroencephalogram (EEG)
- Electroculogram (EOG)
- Fingertip Skin Temperature (SKT)
- Fingertip skin resistance
- Photoplethysmogram (PPG)
- Skin conductance level, and
- Motion Aftereffect (MAE) probe [22].

The research literatures result simulator sickness from nausea/ oculomotor/ disorientation/ SSQ total scores [9, 14, 25, 30, 31], optokinetic stimulation [10, 12], balance [7, 26], visual fatigue (eyestrain, general discomfort, nausea, focusing difficulty and headache) [32].

After the study, researcher should ask open-ended questions aimed at determining whether the subjects were aware of what was being studied, and whether these beliefs biased their response [17]. The symptoms of eye strain recover in a short time, although other symptoms still remain [26] then suggest that questionnaire or measurement method should be done very soon after the experiment. Moreover, to ensure the safety and comfort of participants who view moving images, it is most important to be sensitive to the factors of General Discomfort, Nausea and Headache.

Virtual reality can apply in clinical psychology as treatment of anxiety disorders [33] that useful to significantly reduce phobic fears and increase the perceived efficacy of the participants to effectively cope with the feared stimuli, the application to use virtual environments for treating the fear of heights [34], and therapy for the treatment of body image disturbances in binge eating disorders [35], etc.

4.5.2 Analysis methods

4.5.2.1 Student's *t* test

In 1908 William Sealy Gosset, an Englishman publishing under the pseudonym Student, developed the *t* - test and *t* distribution. The *t* distribution is a family of curves in which the number of degrees of freedom (the number of independent observations in the sample minus one) specifies a particular curve. As the sample size (and thus the degrees of freedom) increases, the *t* distribution approaches the bell shape of the standard normal distribution. In practice, for tests involving the mean of a sample of size greater than 30, the normal distribution is usually applied [36].

It is usual first to formulate a null hypothesis, which states that there is no effective difference between the observed sample mean and the hypothesized or stated population mean — i. e., that any measured difference is due only to chance. In an agricultural study, for example, the null hypothesis could be that an application of fertilizer has had no effect on crop yield, and an experiment would be performed to test whether it has increased the harvest. In general, a *t* - test may be either two-sided (also termed two-tailed), stating simply that the means are not equivalent, or one-sided, specifying whether the observed mean is larger or smaller than the hypothesized mean. The test statistic *t* is then calculated. If the observed *t* - statistic is more extreme than the critical value determined by the appropriate reference distribution, the null hypothesis is rejected. The appropriate reference distribution for the *t* - statistic is the *t* distribution. The critical value depends on the significance level of the test (the probability of erroneously rejecting the null hypothesis).

Using the formula for the t-statistic, the calculated t equals [37]

$$t = \frac{\bar{x}-\mu}{s/\sqrt{n}} \tag{4.1}$$

When :

sample mean: $\bar{x} = \frac{\sum x_i}{n}$,

population mean: μ, (an important use of the sample mean $\bar{x}$ is as an estimator of the unknown population mean μ) ,

variance of sample: $s^2 = \frac{\sum(x_i-\bar{x})^2}{n-1}$,

sample standard deviation s is the positive square root of s^2 , and for random samples of size n from a normal population.

For a two-sided test at a common level of significance $\alpha = 0.05$, the critical values from the t distribution on 24 degrees of freedom are −2.064 and 2.064. The calculated t does not exceed these values, hence the null hypothesis cannot be rejected with 95 percent confidence. (The confidence level is $1 - \alpha$.)

Student's 't' test is probably still the most popular of all statistical tests. The test compares two mean (average) values to judge if they are different or not. The Student's 't' test is the most sensitive test for interval data, but it also requires the most stringent assumptions. The variables/data are assumed to be normally distributed.

The following 't' tests are commonly used :

1. The mean (test) of a single group is compared with a hypothetical value (control).

2. Paired t

When the 'paired design' is used, paired t is applied (e.g. measured before (control) and after (test) a drug administration in a single group of 10 subjects)

3. Unpaired t

For comparing two individual groups (e.g. Height of two groups of 10 subjects each)

4.5.2.2 Principal component analysis

Principal component analysis (PCA) is a mainstay of modern data analysis [38]. PCA can compute a linear transformation that map data from high dimensional space to lower dimensional space. The goal of PCA is to reduce the dimensionality of the data while retaining as much as possible of the variation present in the original data. The best low-dimensional space can be determined by the best eigenvector of the covariance matrix of x. When the eigenvector corresponding to the largest eigenvalues, it also called the "principal components". In geometrical interpretation, PCA projects the data along the directions where the data varies the most. These directions are determined by the eigenvectors of the covariance matrix corresponding to the largest eigenvalues. Moreover, the magnitude of the eigenvalue corresponds to the variance of the data along the eigenvector directions.

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Chapter 5

Experiments and discussions

The experimental conditions of these studies were based on literature reviews that previously stated in Chapter 1, and all experiments followed the guidelines from Chapter 4. Details of the experiments are shown in Table 5.1.

Table 5.1 Experimental conditions and factor effects study.

Exp.	IVE conditions	Factor effect studied	No. of subjects	Duration of Exp. (min.)	Original paper
Exp.1	One-screened & Three-screened IVE	One-screened/Three-screened Parallax, age,	23	2	[1]
Exp.2	Three-screened IVE by using wide-road content	Parallax, position, age, height difference, and nationality	28	4	[2]
Exp.3	Three-screened IVE by using narrow-road content	Position, height difference and age,	15	5	[3]
Exp.4	Three-screened IVE by using narrow-road content	Parallax, position, height difference and age	33	5	[4]

Experiment 1-3 use SSQ to measure the sickness from virtual environment and experiment 4 uses both SSQ and ECG for measurements.

5.1 Experiment 1

5.1.1 Hypotheses

The experiment 1 hypotheses are;

1) three-screened is better than one-screened,

2) parallax 2.0 cm is better than 6.5 cm, and

3) the older subject prone to get a higher simulator sickness.

5.1.2 Experimental settings

The experiment 1 was conducted using a HoloStage™ system in Shonan, Tokai University, as shown in Fig. 5.1. The HoloStage™ was 4.0 × 2.0 × 2.0 meters that are placed in the front, on the right, and on the floor. The system consists of five stereoscopic channels eye-tracked projection system powered by the VR4MAX extreme multi-channel rendering software. Currently, this HoloStage™ system is no longer in used.

Figure 5.1 HoloStage™ system in Shonan, Tokai University

The procedure was tested by using VR4MAX software to set the parallax for distance between eyes in the scene period. The distance between the eyes is set to 2.0 centimeters (cm) for less parallax distance and 6.5 cm which is the normal distance between human eyes for normal parallax in both one-screened and three-screened HoloStage™ system experiments.

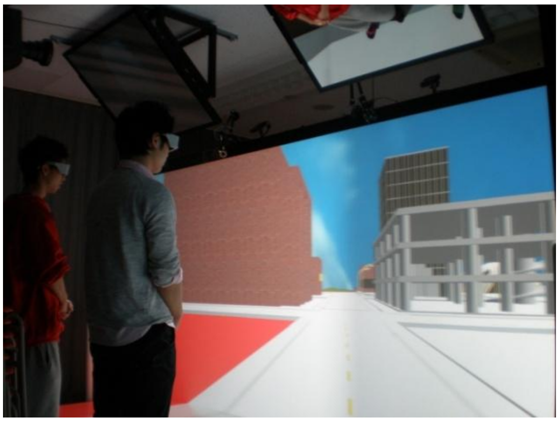


Figure 5.2 Content scene in experiment 1.

The city walkthrough content was used for every subject. The walkthrough scene experiment is shown in Fig. 5.2. This animation included random turn left, turn right and cross the bridge for total two minutes long.

Twenty-three healthy subjects participated in the study. The entire subjects are Japanese students in Tokai University and all of them have experienced in HoloStage™ system. The authors explained purposes and the contents of the study and obtained consent from all subjects. The gender of subjects is irrelevant referred to [5] reported that virtual environment creates the similar effect on both male and female persons. The subjects were divided into 4 groups of testing;

1) One-screened HoloStage™ system with 2.0 cm parallax; 6 subjects (5 male and 1 female) in age between 21-28 years with an age average of 23.67.
2) Three-screened HoloStage™ system with 2.0 cm parallax; 5 subjects (4 male and 1 female) in age between 22-24 years with an age average of 22.80.
3) One-screened HoloStage™ system with 6.5 cm parallax; 6 subjects (5 male and 1 female) in age between 21-26 years with an age average of 22.83.
4) Three-screened HoloStage™ system with 6.5 cm parallax; 6 subjects (6 male) in age between 22-25 years with an age average of 23.33.

One subject group is tested for only one experiment in order to avoid familiarity of the scene due to repeated exposure as suggested in [6].

5.1.3 Results

5.1.3.1 Analysis in mean degree of symptom

The results are evaluated by the famous Simulator Sickness Questionnaire (SSQ) [7-10] for post experiments. The SSQ consist of 16 symptom questions; general discomfort, fatigue, headache, eyestrain, difficulty focusing, increased salivation, sweating, nausea, difficulty concentrating, fullness of head, blurred vision, dizzy (eyes open), dizzy (eye closed), vertigo, stomach awareness and burping. The answer choices are none (0), slightly (1), moderate (2) and severe (3) feeling sickness in each symptom. The percentage in mean of each degree of symptom is shown in Fig. 5.3.

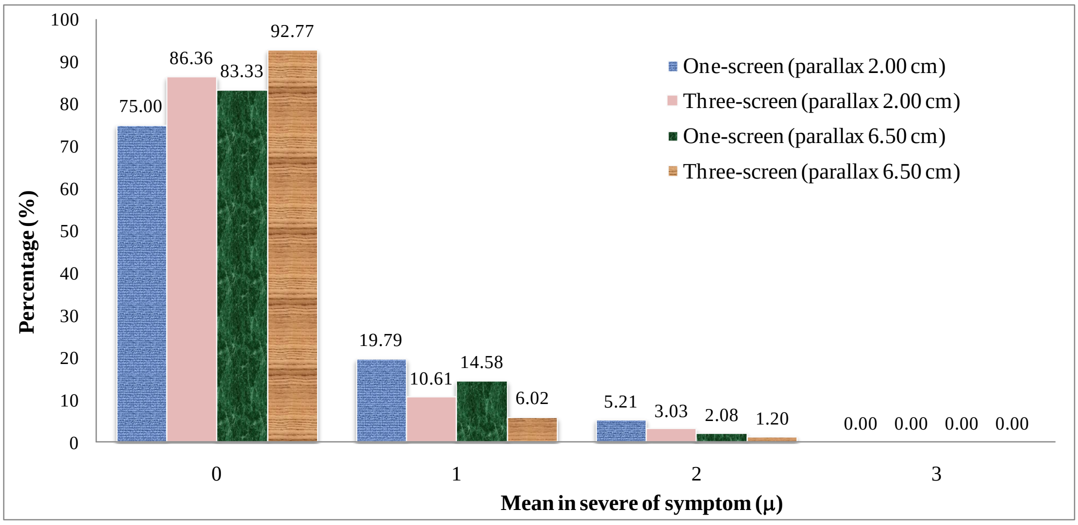


Figure 5.3 The mean of each degree of SSQ symptom
(0, 1, 2, 3; none, slightly, moderate, severe feeling)

For overall 16 SSQ questions, most subjects respond no effect (or 0) as 75.00%, 86.36%, 83.33% and 92.77% represent to group 1, group 2, group 3 and group 4, respectively.

The experiment reports slightly feeling sickness (or 1) as 19.79%, 10.61%, 14.58% and 6.02% and moderate sickness (or 2) as 5.21%, 3.03%, 2.08% and 1.20% in order of group 1, group 2, group 3 and group 4, respectively. Moreover, nobody responds for severe symptom (or 3) in SSQ.

5.1.3.2 Analysis in sixteen questions

Mean (μ) and Standard Deviation (SD) from weighted number of subjects in each group for sixteen equations are shown in Fig. 5.4. The three highest-means of the one-screened system with 2.0 cm parallax comes from general discomfort and fatigue (μ=0.83), fullness of head (μ=0.67) and difficulty concentrating (μ=0.50). While reporting no symptom for headache, increased salivation, sweating and burping.

Three highest-means for the three-screened system with 2.0 cm parallax are from eyestrain (μ=1.00), general discomfort and headache (μ=0.80) and fullness of head and blurred vision (μ=0.60). While reporting no symptom of vertigo, stomach awareness and burping.

The three highest-means of the one-screened system with 6.5 cm parallax are from general discomfort (μ=0.83), eyestrain (μ=0.50) and vertigo (μ=0.33). While reporting no symptom for headache, sweating, blurred vision, dizzy (eyes closed) and burping.

The three highest-means of the three-screened system with 6.5 cm parallax comes from fatigue and eyestrain (μ=0.67), general discomfort and difficulty concentrating (μ=0.50) and difficulty focusing (μ=0.33). While reporting no symptom for sweating, nausea, dizzy (eye open), stomach awareness and burping.

However, Fig.5.4 shows graph with high standard deviation indicates the data is spread out over a wide range of values or just few subjects have prestige severe feelings.

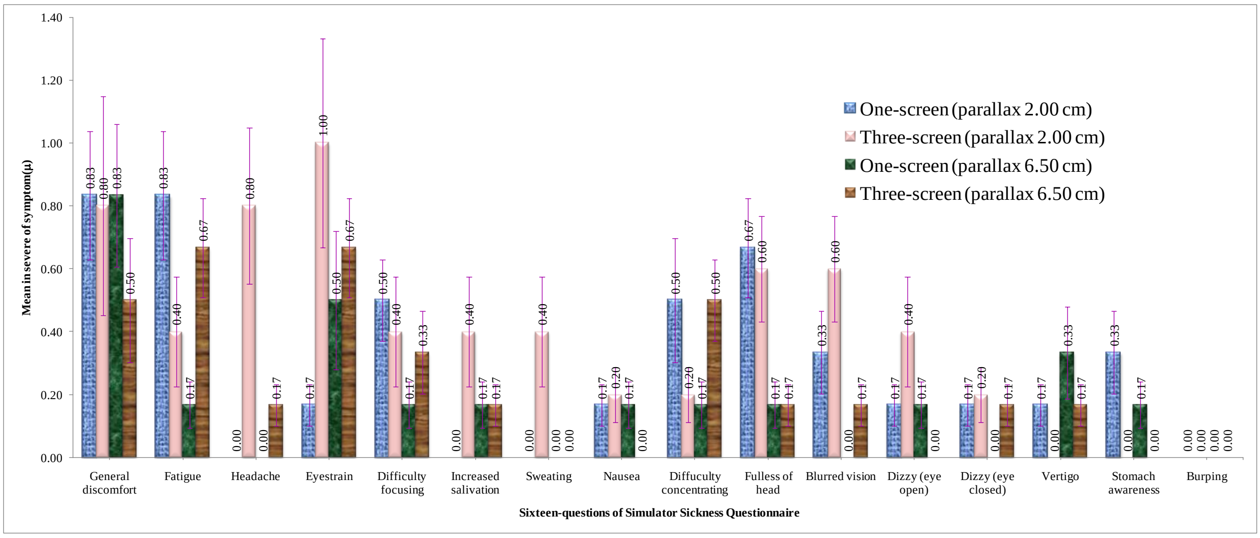


Figure 5.4 Mean of sixteen questions for experiment 1 results.

5.1.3.3 Analysis in Nausea, Oculomotor and Disorientation

Group the symptoms from the questionnaire to three distinct symptom clusters [7], by grouping the symptom increased salivation, nausea, stomach awareness and burping as *Nausea* (N), symptom headache, eyestrain, difficulty focusing and blurred vision as *Oculomotor* (O), and symptom dizzy (eye open), dizzy (eye closed) and vertigo as *Disorientation* (D). The average score of three distinct symptom clusters is shown in Fig. 5.5.

The most effect for the mean of degree of symptom for one-screened system with 2.0 cm parallax is oculomotor (μ=0.25), more than disorientation (μ=0.17) and more than nausea (μ=0.13) or (O>D>N).

The most effect for the mean of degree of symptom for three-screened system with 2.0 cm parallax is oculomotor (μ=0.60) that outstanding highest, more than disorientation (μ=0.20) and more than nausea (μ=0.15) or (O>D>N).

The oculomotor is the highest in simulator sickness (SS) because subject simultaneously sees a natural scene in the real world, but they see alternative view (left-right-left-right views) in the 3D scene. There are two necessities for simulator sickness; 1) functioning vestibular system (the set of canals, tubes, etc. in the inner ear that gives us a sense of orientation and acceleration), and 2) sense of motion. The mismatch between visual motion cues and physical ones, as perceived by the vestibular system is the reason on simulator sickness.

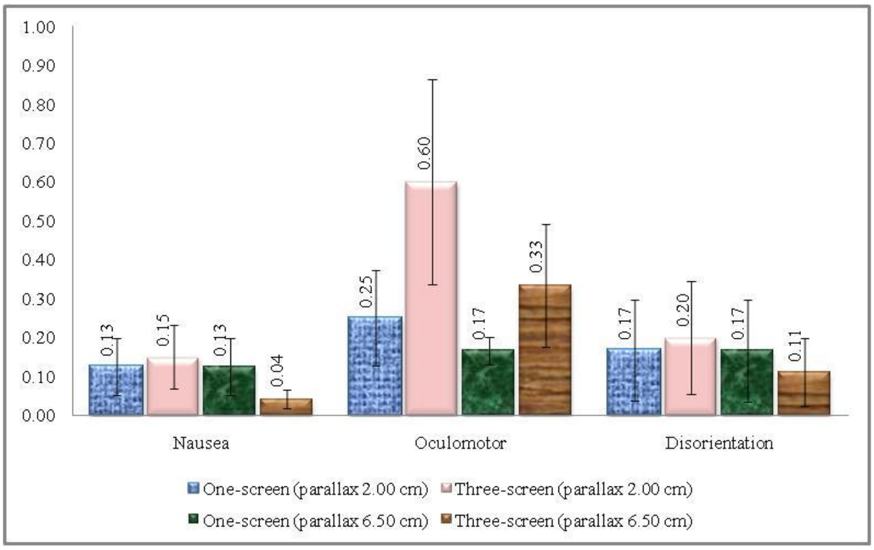


Figure 5.5 The comparative results between three distinct symptom clusters.

The most effect for the mean of degree of symptom for one-screened system with 6.5 cm parallax is oculomotor and disorientation (μ=0.17) and more than nausea (μ=0.13) or ((O=D)>N).

The most effect for the mean of degree of symptom for Three-screened system with 6.5 cm parallax is oculomotor (μ=0.33), more than disorientation (μ=0.11) and more than nausea (μ=0.04) or (O>D>N).

5.1.3.4 Student's *t* test evaluation

The results of four experimental groups; one-screened/parallax 2.0 cm, one-screened/parallax 6.5 cm, three-screened/parallax 2.0 cm and three-screened/parallax 6.5 cm are evaluation by t - test, two tailed type, to indicate the significant difference on simulator sickness between each group in sixteen questions and Nausea, Oculomotor and Disorientation cluster. The JMP® 9.0.2 is used for experimental results analysis in Student's t test.

(a) Analysis in sixteen questions

The set α=0.05 then t=2.0003. Fig. 5.6 shows mean on simulator sickness in sixteen questions of each group experiment that connected with black line on blue vertical bar of standard error plot. Average mean of four groups is 0.30 ±0.13.

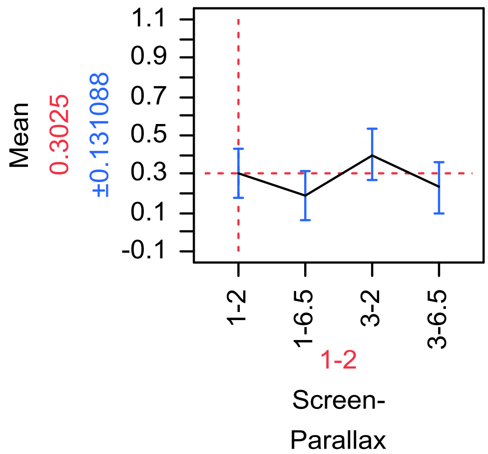


Figure 5.6 Comparative relation between mean of screen-parallax pairs in sixteen questions

The symbol letter in Table 5.2 shows that groups not connected by same letter have significant difference. Therefore, either first three groups above or last three groups below of Table 5.2 do not have significant difference on simulator sickness. Only the simulator sickness result of three-screened/parallax 2.0 cm and one-screened/parallax 6.5 cm has significant difference.

Table 5.2 Evaluation between groups in sixteen questions

Group	Symbol		Least Sq Mean
Three-screened /Parallax 2.00 cm	A		0.40
One-screened /Parallax 2.00 cm	A	B	0.30
Three-screened /Parallax 6.50 cm	A	B	0.23
One-screened /Parallax 6.50 cm		B	0.19

(b) Analysis in Nausea cluster

In Nausea cluster, $\alpha=0.05$ then t=2.17881 for t - test. The mean of four groups is 0.13±0.15 as shown in Fig.5.7.

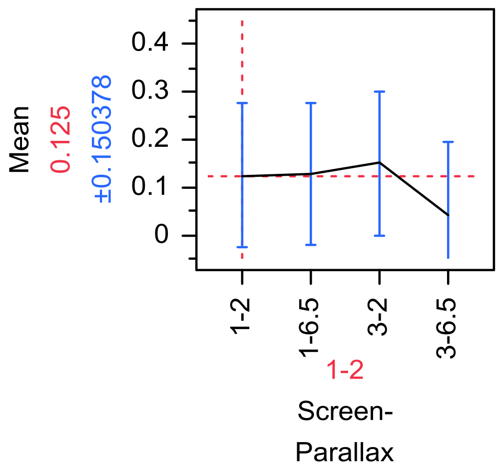


Figure 5.7 Comparative relation between mean of screen-parallax pairs in Nausea cluster

Results in Table 5.3 shown that every group is connected with the same letter, and then four groups do not have significant differences on simulator sickness in Nausea cluster.

Table 5.3 Evaluation between groups in Nausea cluster

Group	Symbol	Least Sq Mean
Three-screened /Parallax 2.00 cm	A	0.15
One-screened /Parallax 6.50 cm	A	0.13
One-screened /Parallax 2.00 cm	A	0.13
Three-screened /Parallax 6.50 cm	A	0.04

(c) Analysis in Oculomotor cluster

In Oculomotor cluster, α=0.05 then t=2.17881 for t - test. Fig.5.8 shows mean of four groups is 0.25±0.26.

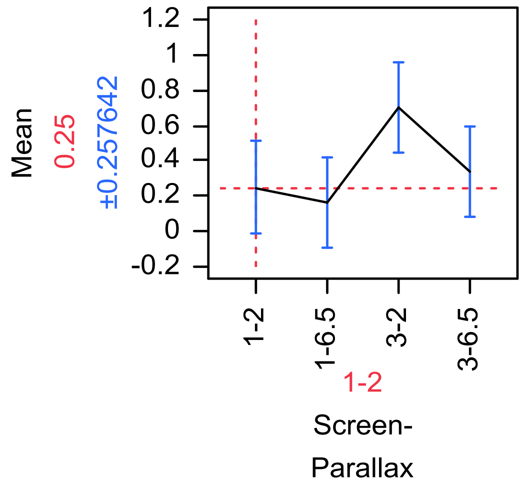


Figure 5.8 Comparative relation between mean of screen-parallax pairs in Oculomotor cluster

Results in Table 5.4 shown that only three-screened/parallax 2.0 cm has significant difference from the others three-screened/parallax 6.5 cm, one-screened/parallax 2.0 cm and one-screened/parallax 6.5 cm that do not have significant difference on simulator sickness in Oculomotor cluster.

Table 5.4 Evaluation between groups in Oculomotor cluster

Group	Symbol		Least Sq Mean
Three-screened /Parallax 2.00 cm	A		0.70
Three-screened /Parallax 6.50 cm		B	0.34
One-screened /Parallax 2.00 cm		B	0.25
One-screened /Parallax 6.50 cm		B	0.17

(d) Analysis in Disorientation cluster

In Disorientation cluster, α=0.05 then t=2.30600 for t - test. Fig. 5.9 shows mean of four groups is 0.17±0.18.

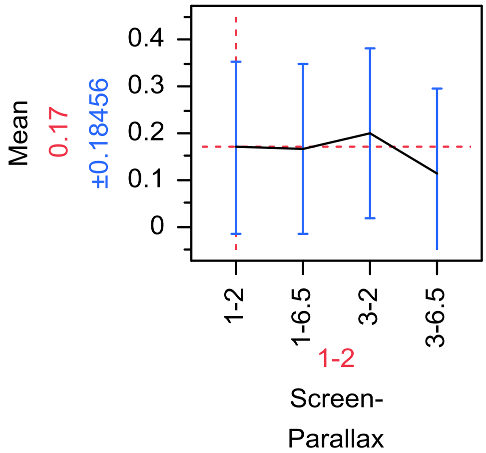


Figure 5.9 Comparative relation between mean of screen-parallax pairs in Disorientation cluster

Results in Table 5.4 shown that every group is connected with the same letter, and then four groups do not have significant differences on simulator sickness in Disorientation cluster.

Table 5.5 Evaluation between groups in Disorientation cluster

Group	Symbol	Least Sq Mean
Three-screened /Parallax 2.00 cm	A	0.20
One-screened /Parallax 2.00 cm	A	0.17
One-screened /Parallax 6.50 cm	A	0.17
Three-screened /Parallax 6.50 cm	A	0.11

5.1.3.5 Screen effect and parallax effect

The factor shown to most significantly affect simulator sickness in experiment 1 was parallax. Table 5.6 shows the SSQ total scores of each factor in mean, standard deviation, minimum, and maximum value. Parallax 2.0 cm produced more simulator sickness than parallax 6.5 cm 44.20% of the mean of the SSQ total score.

Table 5.6 SSQ total scores of parallax, screen and age effect from experiment 1.

	Factor	Mean	SD.	Min.	Max
Parallax	2.0 cm	31.28	29.32	0.00	74.80
	6.5 cm	17.45	17.85	0.00	44.88
Screen	One-screened	22.44	21.87	0.00	71.06
	Three-screened	25.84	28.06	0.00	74.80
Age	21-22 years (n=11)	19.38	22.18	0.00	74.80
	23-24 years (n=7)	25.11	31.86	0.00	71.06
	25-28 years (n=5)	32.91	19.68	0.00	48.62

The second most significant factor effect on simulator sickness was the number of display screens, where three-screened caused higher sickness than one-screened for 13.16% in mean of the SSQ total score. Finally, the third factor effect was age. The mean of SSQ total score was calculated per age group basis.

Although a larger population, the group 21-22 year olds (n=11, when 'n' is number of subjects; mean 19.38) suffered simulator sickness less than the group of 23-24 year olds (n=7; mean 25.11) and less than the group of 25-28 year olds (n=5; mean 32.91).

5.1.3.6 Principal component analysis results

Experiment 1-4 results were analyzed using principal component analysis (PCA) to determine the significance of each factor effect to simulator sickness. The JMP® 9.0.2 was used for analysis. Factor loading with rotation were calculated from mean on simulator sickness of each factor.

The factors affecting simulator sickness and factor loading with rotation are shown in Table 5.7. The SSQ total score that is shown in factor loading analysis was calculated from Table 3.2 in Chapter 3.

The highest rotated factor loadings of the factor groups are considered to be the significantly strongest factor effect on simulator sickness. Height difference was calculated from the height difference between passenger and driver in each three-subject group.

Table 5.7 PCA results in parallax, screen and age factors from experiment 1.

Factor	Rotated factor loading			Eigen value	Percent
	Factor 1	Factor 2	Factor 3		
Parallax	0.996	0.038	0.085	1.350	45.022
Screen	0.040	0.985	-0.171	1.050	34.982
Age	0.089	-0.172	0.981	0.600	19.996

In experiment 1, the most important factor effects on simulator sickness in descending order are parallax (45.022%), number of screens (34.982%) and age (19.996%), respectively.

5.1.4 Discussions

The experimental results show the most factor effect in descending order are parallax, number of display screen, and age. Three-screened induced simulator sickness less than one-screened when comparing in the average sickness score. However, Table 5.5 shown the nausea, disorientation, especially oculomotor were affected simulator sickness from three-screened with parallax 2.0 cm more than one-screened.

Parallax 6.5 cm as the normal distance between human eyes is decreased simulator sickness more than parallax 2.0 cm, as shown in Fig. 5.3 and Table 5.1. Normally, 2.0 cm parallax is usually used in a consumer 3D video camera (for example, Panasonic HDC-TM750 and VW-CLT1), but this parallax is not suited with IVE. Conversely, parallax 2.0 cm is too less to feel appropriate 3D sense in immersive virtual environment. Therefore, the parallax should be set at 6.5 cm in IVE system. On the other hand, the comparative results between three distinct symptom clusters from Fig. 5.5 shows three-screened with parallax 2.0 cm effect on simulator sickness more than one-screened system in oculomotor.

The top-three highest simulator sicknesses are eyestrain, general discomfort and fatigue, consecutively. The subject responds sweating in only three-screened with 2.0 cm parallax case, also with the highest score for eye strain. None of the subjects report for burping or feel severe sickness in every symptom.

The highest effect of subjects comes from oculomotor, and are more than the disorientation and more than the nausea ($O > D > N$). This result represents "seeing" is the most important problem for the virtual environment. Moreover, the older subject prone to get highersimulator sicknessthan younger one.

5.1.4.1 New findings from the results

The new finding from the results is parallax 6.5 cm has got less simulator sickness than parallax 2.0 cm.

5.1.4.2 Observation of the results

We observed that

1) maybe the other factors also relate to simulator sickness, e.g. driver and passenger position, content image distortion, subject’s height/ age/ nationality, and

2) maybe larger parallax is better than smaller parallax. Therefore, the parallax effect will be continued study in experiment 2.

5.2 Experiment 2

5.2.1 Hypotheses

The experiment 2 is to study more factor effect on simulator sickness. The hypotheses and objective are;

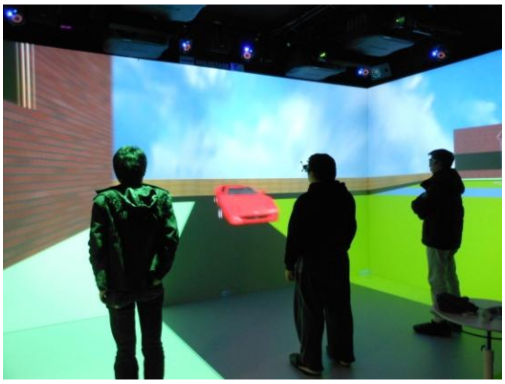
1) parallax 6.5 cm is better than 2.0 and 9.0 cm

2) passenger position is worse than driver position (because of distortion around border), and 3) study nationality effect.

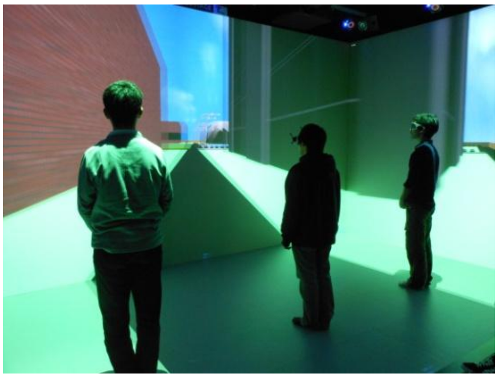
5.2.2 Experimental settings

The HoloStage™ system that used in experiment 2-4 is in Takanawa campus, Tokai University. The screens (5.4m × 3.0 m × 3.0m) are placed in the front, on the right, and on the floor and also using VR4MAX software to set parallax distance in the experiments.

(a) The wide road content in experiment 2.



(b) The narrow road content in experiment 3.



(c) The narrow road content with height difference effect study in experiment 4.

Figure 5.10 Experimental contents in experiment 2-4.

Experiment 2 studied the effects of different parallax on simulator sickness. VR4MAX software was used to set the parallax at 2.0 cm (common parallax for 3D image in commercial cameras), 6.5 cm (normal distance between human left and right eyes), and 9.0 cm (severe parallax). The three-screened HoloStage™ system was used to display a wide-road animation city walkthrough for four minutes. The environment of experiment 2 is shown in Fig 5.10 (a). Subjects were randomly divided but grouped by females or males and nationality first. Three subjects entered at one time, one as a driver (center position) and two as passengers (left and right positions).

This experiment studied the effects upon simulator sickness of different parallax (2.0 cm, 6.5 cm, and 9.0 cm), subjects' positions (driver in center position and passenger in left/right position), subjects' height differences between the driver and passenger, nationality between Japanese and Thai, and subjects' ages.

In experiment 2, subjects were 14 Japanese and 14 Thai, 20 males and 8 females, ages 19-37 years (mean 23.61 years; standard deviation ±5.11), height 152-181 cm (mean 168.89 cm; standard deviation ±7.61).

5.2.3 Results

5.2.3.1 Parallax, position, height difference, nationality, and age effect

The factor which most affected on simulator sickness in experiment 2 was the parallax effect. In experiment 2, parallax 2.0 cm, 6.5 cm, and 9.0 cm were studied. Table 5.8 shows the highest SSQ total score in descending order were related to parallax 9.0 cm (mean 71.89), parallax 2.0 cm (mean 56.52) and parallax 6.5 cm (mean 48.62), respectively.

Table 5.8 SSQ total scores of parallax, position, heigh difference, nationality and age effects from experiment 2.

	Factors	SSQ total scores			
		Mean	STD	Min	Max
Parallax	2.0 cm	56.52	30.75	0.00	89.76
	6.5 cm	48.62	28.92	3.74	82.28
	9.0 cm	71.89	28.22	33.66	119.68
Position	Left	57.76	28.43	11.22	93.50
	Center	56.47	36.45	0.00	119.68
	Right	61.92	26.25	3.74	100.98
Height diff	Plus (+)	65.72	21.14	33.66	93.50
	Zero	56.47	36.45	0.00	119.68
	Minus (-)	56.10	29.97	3.74	100.98
Nationality	Japanese	58.50	26.51	3.74	119.68
	Thai	58.77	33.91	0.00	100.98
Age	19-20 years (n=10)	61.34	28.60	11.22	100.98
	21-23 years (n=9)	44.88	27.99	0.00	78.54
	24-37 years (n=9)	69.40	30.90	3.74	119.68

The second strongest factor effect relating to simulator sickness was the subject's position. SSQ total scores in descending order were the right position (mean 61.92), left position (mean 57.76), and center position (mean 56.47).

The third greatest factor effect was the height difference between driver and passenger. In cases where the passenger was taller than the driver or a plus sign (+) group is shown, the passenger suffered greater sickness (mean 65.72) than the driver (mean 56.47). On the other hand, when the passenger was shorter than the driver or minus sign (-) group (mean 56.1), the passenger experienced less sickness.

Although the fourth factor effect is a nationality, the SSQ total score mean is very similar (only 0.45% difference) between Japanese (mean 58.54) and Thai (mean 58.77). This research suggests to repeat testing with a greater population and various nationalities.

The last factor measured relating to simulator sickness in this experiment was age. The mean of SSQ total scores of each age group was calculated from most similar population between age group. The group of 21-23 year olds (n=9; mean 44.88) suffered simulator sickness less than the group of 19-20 year olds (n=10; mean 61.34) and less than the group of 24-37 year olds (n=9; mean 69.39).

5.2.3.2 Principal component analysis results

The SSQ total scores data were calculated in PCA from each subject. However, SSQ total scores of "age" and "height difference" are grouped for expedient representation. Height difference factor was calculated from height difference between passenger (in left or right position) and driver (center position). A value of plus sign (+), zero (0), or minus sign (-) was assigned to the passenger who was taller than the driver, the driver or the passenger who had the same height as the driver, and the passenger who was shorter than the driver, respectively.

Table 5.9 PCA results in parallax, position, height difference, nationality and age factors from experiment 2.

Factor	Rotated factor loading					Eigen value	Percent
	Factor 1	Factor 2	Factor 3	Factor 4	Factor 5		
Parallax	0.991	0.001	0.014	-0.044	-0.124	1.387	27.742
Position	0.001	0.992	-0.055	0.013	-0.109	1.246	24.929
Height diff	0.014	-0.055	0.990	0.125	-0.026	1.034	20.670
Nationality	-0.045	0.013	0.126	0.987	-0.084	0.719	14.383
Age	-0.128	-0.113	-0.027	-0.086	0.981	0.614	12.276

Table 5.9 shows the most important factor effects on simulator sickness in descending order are parallax (27.742%), position (24.929%), height difference (20.670%), nationality (14.483%), and age (12.276%).

5.2.4 Discussions

Experiment 2 results are;

1) Parallax effect onsimulator sicknessfrom 6.5 <2.0<9.0 cm,

2) Position effect on simulator sickness from driver<passenger, and

3) No nationality effect.

5.2.4.1 New findings from the results

The new finding from the results is a passenger that is taller than driver gets a higher SS. (This result will be confirmed in experiment 3.)

5.2.4.2 Observation from the results

The wide-road does not show distortion around the screen border area. Then in experiment 3, the content is changed to narrow - road content that add more details and more bright color around the border area in order to check the driver and passenger position effects.

5.3 Experiment 3

5.3.1 Hypotheses

The experiment 3 changed wide-road content to narrow-road content to confirm study on position effect. Experiment 3 hypotheses are;

1) position effect onsimulator sicknessfor the driver (center) <passenger (left) <passenger (right) and

2) passenger that is taller than driver gets a highersimulator sickness(re-confirmation).

5.3.2 Experimental settings

In this experiment, a new subject group was attended and the driver versus passenger position effect was again studied using the HoloStageTM system. However, the content displayed on the screens was changed from a wide- to a narrow-road animation city walk-through that added more details and multiple colors on the sides of the roads, and thus, on the lower borders of the screen. The scene is shown in Fig. 5.10 (b). Although this narrow-road content is brighter than the wide-road content in Fig.5.10 (a), the illuminance (the light power of a source as perceived by the human eye measure per unit area, as Lux) is very low (maximum only 40 Lux that is similar with home low-lighting condition) then this brightness is probably not effect to simulator sickness.

The city walk-through animation randomly turned left and right, and walked up and down bridges for five minutes. Subjects were randomly divided after first being grouped by gender. Three subjects entered at a time, one as the driver (center position) and two as passengers (left and right positions).

In experiment 3, the effects of the subject's position (driver in center position and passengers in left/right position), the difference in the subjects' heights, and the subjects' ages on simulator sickness were studied.

Fifteen subjects are Tokai University students, 11 males and 4 females, ages 22-34 years (mean 24.13 years; standard deviation ±3.72), height 154-178 cm (mean 168.47 cm; standard deviation ±7.22).

5.3.3 Results

5.3.3.1 Position, height difference and age factor

Position was the most significant factor effect on simulator sickness in the experiment 3 results. As can be seen in Table 5.10, simulator sickness of the driver in center position (mean 50.86) was slightly less than the passenger in the left position (mean 53.11) and significantly less than the passenger in the right position (mean 91.26). This result indicates the driver position is the best position in IVE for the most natural scene view and thus, less sickness.

Table 5.10 SSQ total scores of position, height difference and age effect from experiment 3.

	Factors	SSQ total scores			
		Mean	STD	Min	Max
Position	Left	53.11	30.20	22.44	93.50
	Center	50.86	26.66	7.48	74.80
	Right	91.26	64.70	14.96	115.94
Height diff	Plus (+)	84.77	89.24	22.44	187.00
	Zero	61.71	35.70	7.48	115.94
	Minus (-)	58.59	30.35	14.96	93.50
Age	22 years (n=10)	56.10	34.64	7.48	115.94
	24-34 years (n=5)	83.03	61.59	29.92	187.00

The second factor effect on sickness was the height difference between the driver and the passenger. Table 5.9 shown passengers who were taller than the driver (height difference is plus) suffered a higher rate of simulator sickness than the driver or passengers who were shorter than the driver (mean 84.77). The passengers who had the same height as the driver and the driver himself (height difference is zero) suffered a lower rate of sickness than passengers who were taller than the driver (mean 61.71). Additionally, the passengers who were shorter than the driver (height difference is a minus) suffered a lower rate of sickness than the driver or passengers who were taller than the driver (mean 58.59).

The last factor effect studied in experiment 3 was age. The group of 24-34 year olds (n=5; mean 83.03) suffered simulator sickness more often than the 22 years olds group (n=10; mean 56.1). These results indicate that older people are more prone to sickness than younger people.

5.3.3.2 Principal component analysis results

In experiment 3, Table 5.11 shows the most important factor effects on simulator sickness in descending order as position (71.595%), height difference (22.006%), and age (6.399%) effects, respectively.

Table 5.11 PCA results of position, height difference and age factors from experiment 3.

Factor	Rotated factor loading			Eigen value	Percent
	Factor 1	Factor 2	Factor 3		
Position	0.968	0.168	0.189	2.148	71.595
Height diff	0.195	0.889	0.415	0.660	22.006
Age	0.240	0.453	0.859	0.192	6.399

5.3.4 Discussions

The results show;

1) position effect onsimulator sicknessof the driver (center) <passenger (left) <passenger (right) and

2) passenger that is taller than driver gets a higher SS.

These results confirm the experiment 2's results.

5.3.4.1 New findings from the results

The new finding from the results is a position effect onsimulator sicknessfor the driver (center) <passenger (left) <passenger (right).

5.3.4.2 Observation of the results

What is the most important factor effect between parallax, position, and height difference? The importance of these factors effect will study in Exp. 4.

5.4 Experiment 4

5.4.1 Hypotheses

Experiment 4 objective is to find the most important factor effect on simulator sickness between parallax, position, and the height difference.

5.4.2 Experimental settings

The objective of this experiment is to study and compare three effects as position, parallax, and height difference effects. The simulator sickness affects by different positions, parallax and height difference were experimented with new subject group in three-screened HoloStage™ system. The content was narrow road walk-through animation as same as content in experiment 3. The content is shown in Fig. 5.10 (c). This experiment was 5 minutes long.

In experiment 4, subjects are 33 students from Tokai University in age between 20-34 years old (mean = 22.76 years; standard deviation ± 3.33). They are 27 males and 6 females, and height 154-186 cm (mean=168.85 cm; standard deviation ±6.84). The author explained the purpose and obtained consent from all subjects before the experiment.

5.4.3 Results

5.4.3.1 Parallax, position and height difference effect

Experiment 4 is studied and compared the significance between parallax, position, and height different effect. The results are cut the irrelevant SSQ and failed ECG signals, therefore only 14 subjects results are used for analysis.

Even though both experiment 2 and 4 results suggest that older subjects are prone to suffer higher rates on simulator sickness than younger subjects, experiment 3 results show the middle age group as having the least amount of sickness. Therefore, these three experimental results were inconclusive regarding the tendency of age to be a factor in causing simulator sickness in IVE. The author suggests future research be conducted using a larger sample group with a wider age range to determine the age effect on simulator sickness.

Table 5.12 SSQ total scores of position, height difference and parallax effects from experiment 4.

	Factors	SSQ total score			
		Mean	STD	Min	Max
Position	Left	30.86	24.64	3.74	123.42
	Center	28.26	24.07	7.48	48.62
	Right	31.17	27.79	0.00	100.98
Height diff	Plus (+)	31.95	28.59	0.00	100.98
	Zero	28.26	24.07	7.48	48.62
	Minus (-)	27.27	25.11	3.74	52.36
Parallax	2.0 cm	30.86	24.60	3.74	52.36
	6.5 cm	30.86	28.01	0.00	100.98
	9.0 cm	30.86	27.00	18.7	123.42

Table 5.12 shows driver in center position had gotten lesssimulator sicknessthan passengers in left, then right positions. The passenger in plus sign group or subject that taller than driver has higher sickness, and no difference in parallax effect from Exp.4 results.

5.4.3.2 Principal component analysis results

Table 5.13 shows Eigenvalues of factors effect from experiment 4 results. The Eigenvalues in percent descending order are height difference (60.60%), position (26.43%), and parallax (12.97%). The highest rotated factor loadings are height difference, position, and parallax, respectively. The total percentage of effect from height difference and position are 87.03%. This result shows the most significant are height different effect, position effect, and parallax effect, respectively.

Table 5.13 PCA results of height difference, position and parallax factors from experiment 4.

Factor	Rotated factor loading			Eigen value	Percent
	Factor 1	Factor 2	Factor 3		
Height diff	0.953	-0.094	0.289	1.818	60.598
Position	-0.0889	0.980	-0.176	0.793	26.434
Parallax	0.309	-0.202	0.929	0.389	12.968

5.4.3.3 Relationship between SSQ and BPM

In experiment 4, the simulator sickness from IVE are measured by both subjective measures as SSQ and physiological measures as BPM from ECG signal. The post-test SSQ is measured immediately or up to 5 minutes after the subject finished experimenting. The ECG signal is measured from rest time (one minute) before the experiment, five minutes during the experiment, and rest time (one minute) after experiment, as shown in Fig. 5.11.

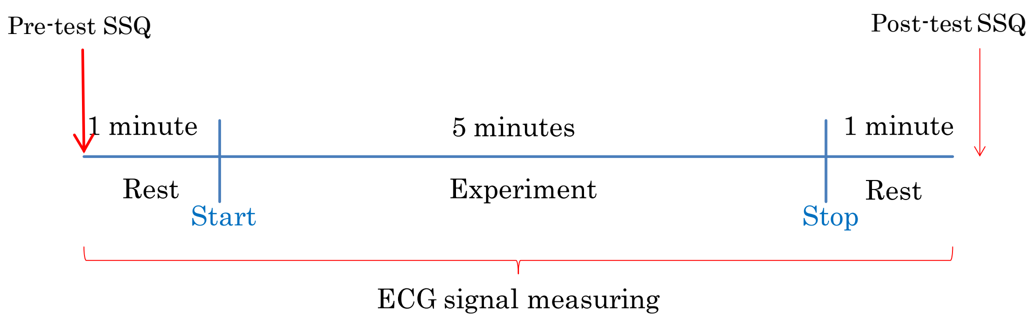
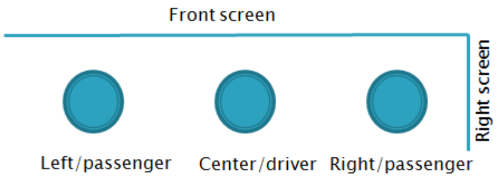


Figure 5.11 SSQ and ECG measured time in experiment 4.



	Parallax	ECG measure positions		
1)	2.0	ECG	ECG (t)	x
2)	6.5	x	ECG	ECG (t)
3)	9.0	ECG (t)	x	ECG

Note: (t) means the position of tallest person of each group.

Figure 5.12 ECG measurement.

The two wireless ECG probes are used for measure 3 subjects in each experiment. Therefore, the ECG measuring was designed for positions shown in Fig.5.12 as 1) parallax 2.0 cm, the ECG signals were measured at passenger in left the position and driver in center position 2) parallax 6.5 cm, the ECG signals were measured at passenger in the right position and driver in center position, and 3) parallax 9.0 cm, the ECG signals were measured at passenger in left and right position. Note that 't' means the position of the tallest subject. Then, only 22 of 33 subjects were measured for ECG signal. Moreover, after discarding the improper ECG signal and match with the SSQ results, only 14 subject's ECG signal is used for evaluation.

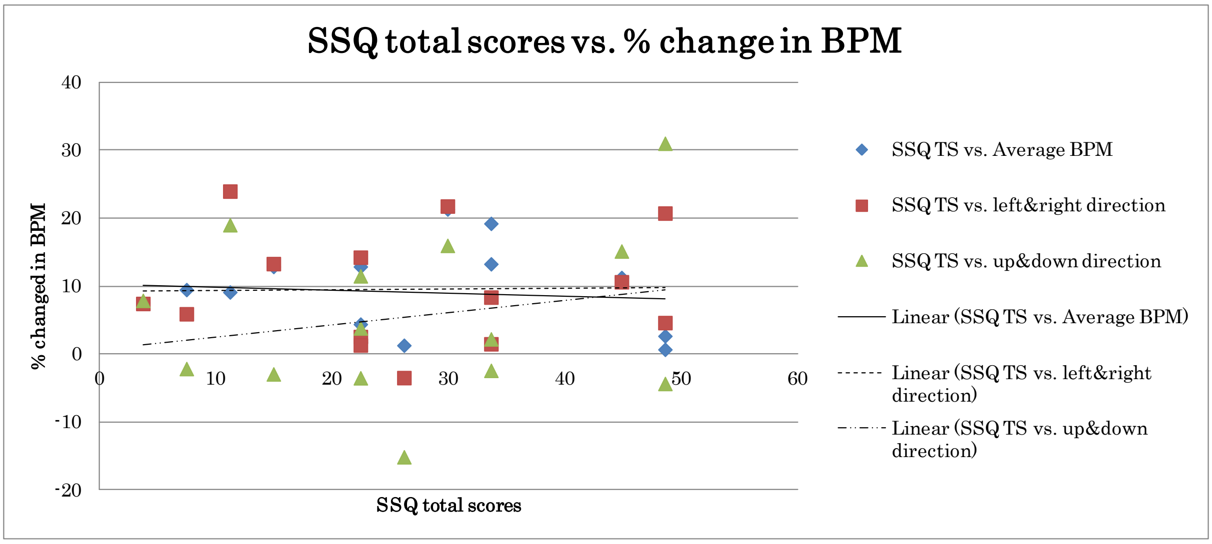


Figure 5.13 SSQ total scores vs. % change in BPM

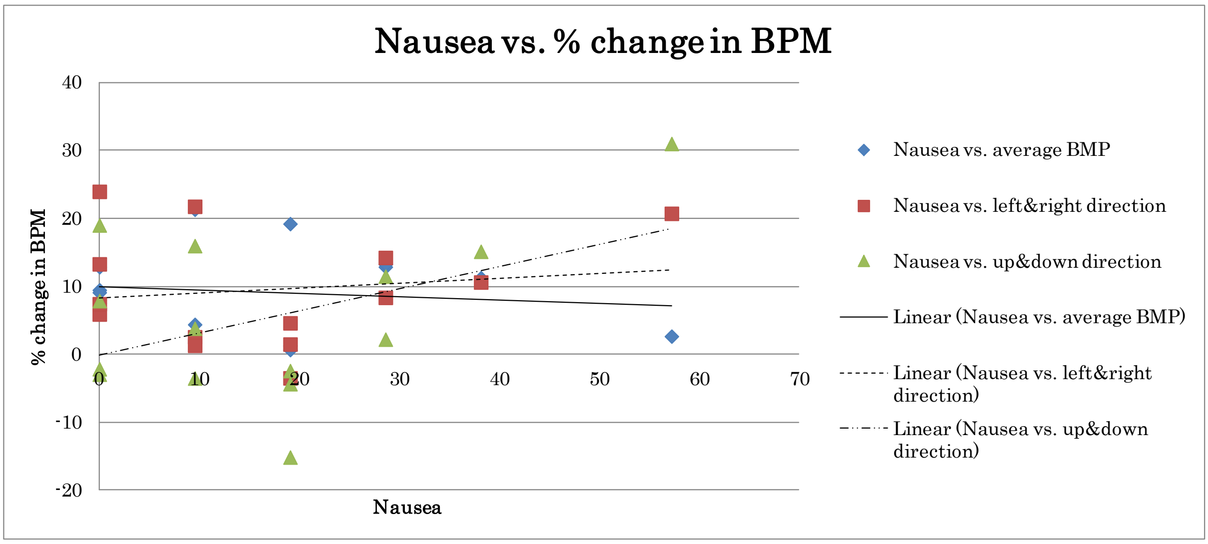


Figure 5.14 Nausea vs. % change in BPM

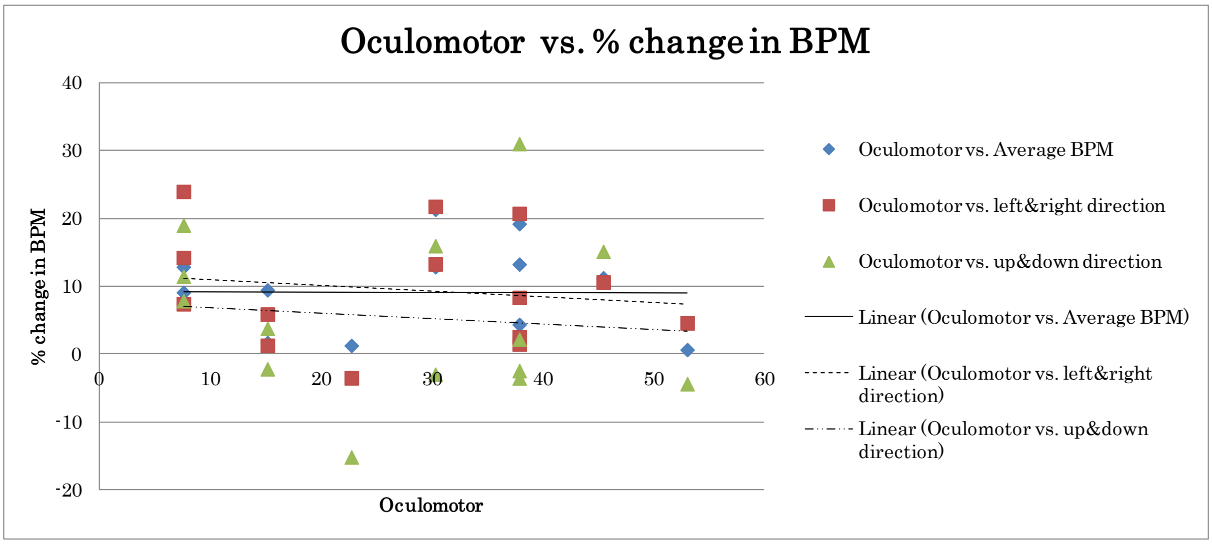


Figure 5.15 Oculomotor vs. % change in BPM

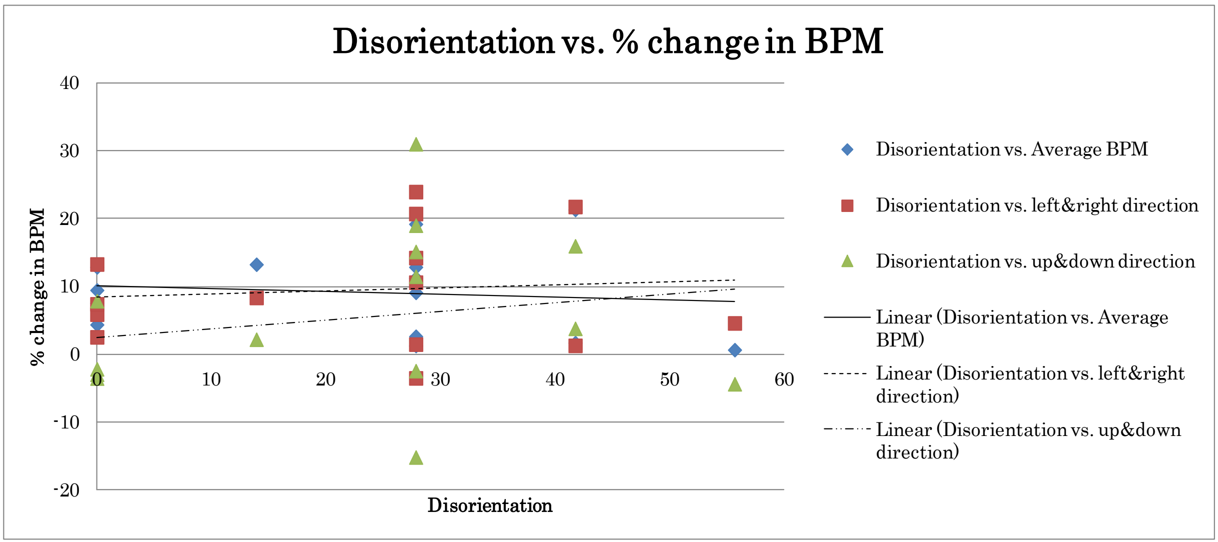


Figure 5.16 Disorientation vs. % change in BPM

The walk-through content included 7 turns left, 8 turns right, and 2 bridges enter. Post-test SSQ results were analyzed in SSQ total scores, nausea, oculomotor, and disorientation groups. Heartbeat results were analyzed in average beat per minute (BPM) from 5 minutes ECG signal (Exp BPM), on turning time average (Turn BPM), and during enter two bridges average BPM (Bridge BPM). Therefore, the relationship between SSQ and BPM are shown in Fig. 5.13- 5.16.

Table 5.14 The correlation coefficient between simulator sickness and BPM.

	BPM avg.	BPM turn	BPM Up-down
SSQ total score	-0.10138 ($0.35<\rho<0.40$)	0.37106 ($0.09<\rho<0.10$)	0.17050 ($0.25<\rho<0.30$)
Nausea	-0.12589 ($0.30<\rho<0.35$)	0.14788 ($0.30<\rho<0.35$)	0.45079 ($0.05<\rho<0.06$)
Oculomotor	-0.01574 ($\rho>0.40$)	-0.14869 ($0.30<\rho<0.35$)	-0.10179 ($0.35<\rho<0.40$)
Disorientation	-0.10922 ($0.35<\rho<0.40$)	0.09325 ($0.35<\rho<0.40$)	0.18736 ($0.25<\rho<0.30$)

The correlation coefficients in Table 5.14 show the strength and the direction of a linear relationship between simulator sickness in SSQ total score, nausea, oculomotor, and disorientation with heartbeat per minute. Nausea is related to heart rate ($0.05<\rho<0.06$; one-tailed) when content is in an up-down direction, but oculomotor and disorientation are not related to heartbeat measurement. However, oculomotor is the largest simulator sickness in 3D scene, when measured by SSQ. Therefore, heart rate in BPM cannot be used to measure oculomotor sickness in 3D scene. This research suggests to use another physiological measurement for IVE experiment, e.g. EOG.

5.4.3.4 Relationship between SSQ / BPM and MSHQ

The motion sickness history questionnaire (MSHQ, Appendix A) was adapted from [11]. The questions are primarily concerned with the subject's susceptibility to motion sickness in carsick. When comparing MSHQ with SSQ, MSHQ is slightly related to the SSQ total score, and highly related with disorientation and oculomotor, but not related with nausea, as shown in Fig.5.17. However, the correlation coefficient between MSHQ and SSQ are not related, as shown in Table 5.15.

Table 5.15 The correlation coefficient between MSHQ and SSQ.

	SSQ total scores	Nausea	Oculomotor	Disorientation
MSHQ	-0.09899 ($0.35<\rho<0.40$)	0.01145 ($\rho>0.40$)	-0.27952 ($0.20<\rho<0.25$)	0.11845 ($0.30<\rho<0.35$)

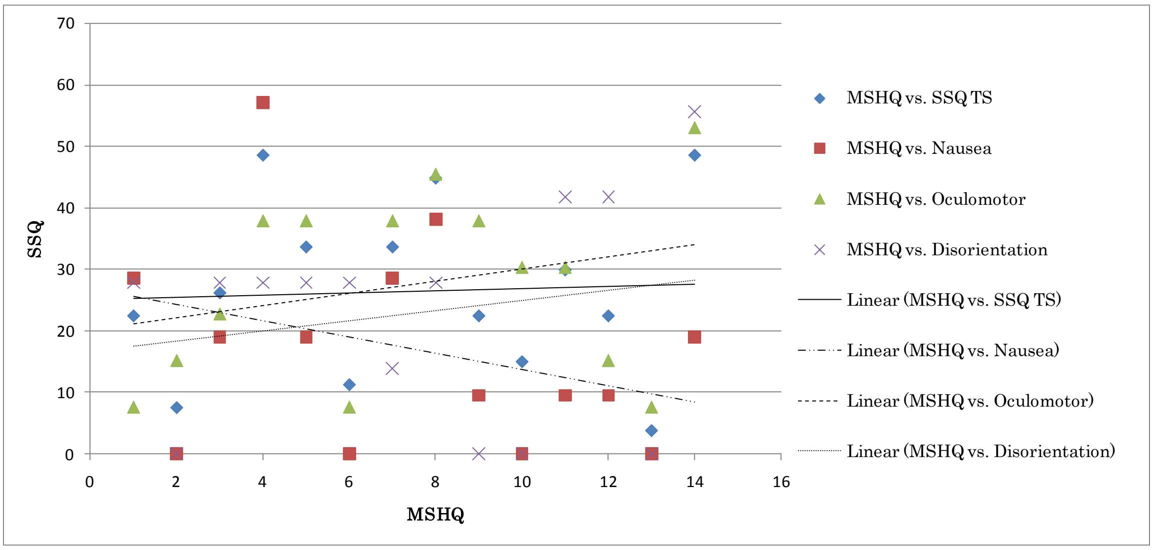


Figure 5.17 MSHQ vs. SSQ total score, Nausea, Oculomotor, and Disorientation.

Figure 5.18 shows MSHQ are related to percent change in BPM in turn left/right direction and in up/down direction. But MSHQ is not related to average BPM results for overall 5 minutes experiment. Moreover, the correlation coefficient in Table 5.16 shows relationship between MSHQ and BPM when content in left & right ($0.04<\rho<0.05$; one-tailed) and up & down ($0.04<\rho<0.05$; one-tailed) directions, but MSHQ is not related to average BPM.

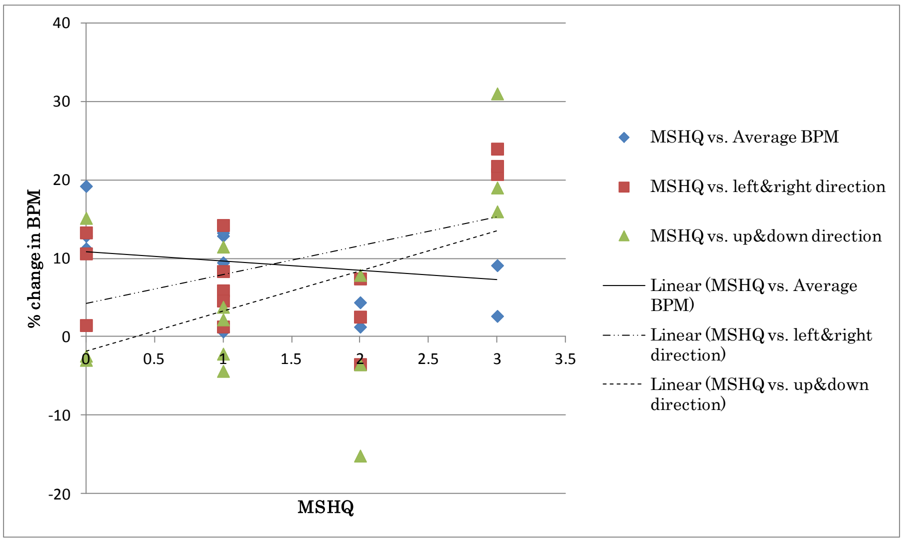


Figure 5.18 MSHQ vs. % change in BPM (average, left & right direction, and up & down direction).

Table 5.16 The correlation coefficient between MSHQ and % change in BPM.

	Average BPM	Left& right direction	Up & down direction
MSHQ	-0.20120 (0.20<ρ<0.25)	0.48080 (0.04<ρ<0.05)	0.46204 (0.04<ρ<0.05)

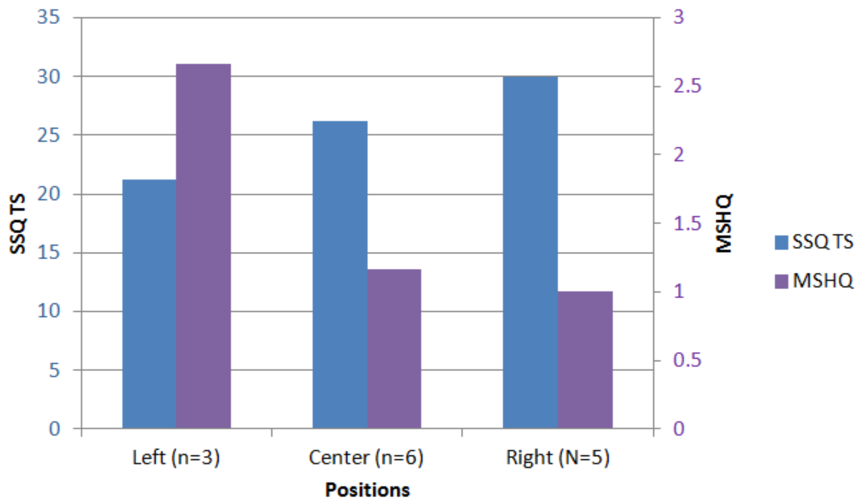


Figure 5.19 MSHQ (left, center and right positions) vs. SSQ TS.

Table 5.17 The correlation coefficient between MSHQ and SSQ TS at left, center and right positions.

	Left	Center	Right
Correlation coefficient	-0.28730 (0.15<ρ<0.20)	0.54795 (0. 02<ρ<0.025)	-0.81215 (ρ<0.0005)

The right position is the most distorted view from several screen border connections. A subject in this position will see an unnatural scene and has highest SSQ total scores. Nevertheless, Fig. 5.19 and Table 5.17 show MSHQ scores in the right position are negatively related to SSQ TS (ρ<0.0005; one-tailed). This correlation means even though the subjects have less experience in motion sickness, but they will feel moresimulator sicknesswhen stay in the right position. On the other hand, the subject will affect from virtual environment setting (e.g. position setting in IVE) more than virtual content. Therefore, the IVE setting is very important to reduce the possibility on simulator sickness.

5.4.4 Discussions

Experiment 4 results show the most important factor order as height difference, position, and parallax. Position and height different are important effects in IVE because they are not influenced by the content. The position effect shows The driver position suffers the least simulator effect. Moreover, the passenger in the left position has got less simulator sickness when compared with the right position. Whereas the passenger who taller than the driver suffer higher simulator sickness. Moreover, this research study the relationship between SSQ and MSHQ. Although subjects have low MSHQ but they suffer higher simulator sickness at the position near screen border connections. Furthermore, from experimental results, nausea is related to heart rate only when content is in an up-down direction, but oculomotor and disorientation are not related to heartbeat measurement. However, oculomotor is the largest simulator sickness in 3D scene, when measured by SSQ. Therefore, heart rate in BPM cannot be used to measure oculomotor sickness in 3D scene. This research suggest to use another physiological measurement for IVE experiment, e.g. EOG.

The new finding from the results are;

1) Oculomotor is largestsimulator sicknessin 3D scene according to SSQ results.

2) The BPM results are only related with nausea when content is in an up-down directions.

5.5 Summary of factor effects on simulator sickness

Experiment 1 studied one-screened and three-screened IVE effect. The three-screened IVE was less effected on simulator sickness but needed attention for setting suitable parameters.

Experiment 2 results shown parallax effect on simulator sickness in ascending order are 6.5 < 2.0 < 9.0 cm.

Experiment 3 results shown position effect on simulator sickness for the driver (center) <passenger (left) <passenger (right) and the passenger who was taller than the driver has got a higher simulator sickness.

Experiment 4 results shown the most important factor order was height difference, position, and parallax. Moreover, the oculomotor was largest simulator sickness in 3D scene according to SSQ results. However, the BPM results were only related with nausea when content was in an up-down directions.

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Chapter 6

Proposal for safety guidelines

In order to decrease the occurrence of simulator sickness according to the findings in this research study, This research proposes the proposal for safety guidelines in immersive virtual environments based on the environmental and human factors as follows.

6.1 Parallax

Experiment 2 and 3 results suggest parallax 6.5 cm is the best for a virtual display in IVE to decrease the possibility of simulator sickness. Parallax 2.0 cm that is used in common commercial 3D camera/TV is not proper for an IVE display. Moreover, even though the 9.0 cm parallax provides more 3D depth for fantastic viewing, but the viewer will experience more simulator sickness due to a severe parallax effect. Therefore, parallax 9.0 cm is not appropriate for display in IVE.

The IVE should set parallax to 6.5 cm, referred to experiment 1-4 results.

The possible reasons are; stereopsis is considered as one of the most important depth cues. The pupils of the two human eyes are shifted by approximately 6.5 cm [1], which causes each ratinal image to provide a slightly different view in the same scene. The brain is able to combine these two views into a single 3D image. Therefore, when the subject enters immersive virtual reality world, the most natural scene should be seen and parallax should be the most similar when eyes see the real world as 6.5 cm.

6.2 Position

The position effect results from experiment 3 and 4 show that the driver position are causing the least amount of simulator sickness because the driver always see the natural scene while the passenger does not. Furthermore, the passenger in right position suffered simulator sickness more than the passenger in the left position, especially when lower screen borders displayed more details and multiple colors (from Tables 5.8 -5.9 in Chapter 5). Regarding to experimental results, this research observed that the right position is closed view of where the screens join together. The distortion that occurs at these border connections might be a main reason for simulator sickness in IVE.

Due to the above findings, this research recommends the best position for less simulator sickness while using an IVE is the driver position. Moreover, passenger should stay near driver, and avoid positioning near screen border connections.

6.3 Number of display screen

From experiment 1 results, the three-screened is higher immerse displayed in immersive virtual environment but need attention to set the proper parameters. When appropriate parameter is set, the best visual scene is displayed. Therefore, the parallax 6.5 cm. should be set for the best display in immersive virtual environments. Even though the three-screened display immerses people more completely into the virtual world, the location where the screens join together provides a non-natural and distorted view. Therefore, it causes more simulator sickness in case of improper parameter setting.

The possible reasons are; the display screen should be wide enough to give the user for the width that they need to obtain proper 3D experience. From human's field of view, the viewer can notice real world when they see one-screened IVE (e.g. they see the real world's floor). Therefore, three-screened is better than one-screened in IVE.

6.4 Height difference

Although subject's height cannot be changed to reduce simulator sickness in an IVE, but a group of people entering simultaneously can choose a driver and passenger positions based on their heights to minimize simulator sickness for them all.

The driver is the best position for decreasing simulator sickness. However, the results in height difference effect show that the passenger who is shorter than the driver suffers less simulator sickness. On the contrary, it is possible for the passenger who is taller than the driver to experience more sickness. Therefore, this research suggests placing the tallest subject in the driver position and the shorter subject in the passenger position.

The possible reasons of simulator sickness are 1) Vestibular function reason. Because the field of view of human is around 180°[2], the bird's eye view will notice the fact that the subject's physical body is not real moving in the animation scene, while the worm's eye view is not seen. Moreover, 2) Psychology reason. The subject might have an anxiety disorder in phobic fear of heights, then they feel sick.

The investigation of gravity effect of simulator sickness, as gravity acts on all parts of the body, one's entire weight can be considered as concentrated at a point where the gravitational pull on one side of the body is equal to the pull on the other side. This point is the body's center of gravity, and it constitutes the exact center of body mass. A tall person falls harder than a short person. For the same reason, the further the body's center of gravity is displaced from the midline of its base of support, the more force is necessary to return it to the balanced position [3]. Therefore, the taller subject might be sick than shorter subject.

The proposed safety guidelines in this research is not related to the content, but they relate to IVE setup (e.g. set tallest subject as a driver position.

This guideline manages subject's height difference in case of more than one subject enter IVE at the same time. This setting is related to biological theory, but not relate to the content). Consequently, these guidelines can be adopted in any content of IVE for future research.

6.5 Safety guidelines for IVE

Regarding to result from multiple factors study on simulator sickness in an immersive virtual environment and investigation of their factor loadings through subject experiments based on a simulator sickness questionnaire, the proposed safety guidelines for IVE in descending order are;

- In the case where two or more subjects enter the immersive virtual environment, the subjects should be set to the same height or set them on adjusted chairs during the experiment.
- In the case where subjects cannot be set in the similar height, the tallest subject should be a driver and the shorter subjects should be passengers.
- The passenger should stay near to the driver and avoid the position near connection of border screens.
- Parallax should set to 6.5 cm.
- Three-screened is better than one-screened in IVE, but need attention to set the proper parameters.
- The subject that has severe motion sickness (e.g. carsick, airsick, seasick) might get severe simulator sickness from the similar virtual content.
- If a researcher wants to check the content effect, the subject that has severe motion sickness in the history should be removed from the experiment.

Bibliography

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[2] H. B. Duh, J. J.W. Lin, R. V. Kenyon, D. E. Parker, and T. A. Furness："Effects of Field of View on Balance in an Immersive Environment", IEEE Proceedings of the Virtual Reality, pp.235-240 (2001)

[3] R. C. Schafer："Clinical Biomechanics：Musculoskeletal Actions and Reactions", Chapter 4, Williams & Wilkins publisher, August (1983)

Chapter 7

Conclusions

Immersive virtual environment (IVE) which use large multiple-screened influence simulator sickness differently than IVE which use a head-mounted display or non-immersive virtual environments which use one large projection screen and a monitor screen. The unique qualities of multiple-screened IVEs provide an immersive experience for simultaneous users while these users see the screen from different positions ("driver" versus "passenger"). This research purposes are studying environmental factor effects on simulator sickness such as position, parallax, and number of display screens, and also subject factor effects such as age, height difference and nationality. The HoloStage™ experiment with various environmental conditions was used with a follow-up simulator sickness questionnaire, motion sickness history questionnaire, and heart rate measurements.

7.1 One-screened and three-screened HoloStage™

Simulator sickness in an immersive virtual environment was investigated according to parallax and the number of screens by using simulator sickness questionnaire. The experiment 1 results show that parallax should be set to 6.5 cm and the most uncomfortable effect in IVE comes from Oculomotor. Moreover, three-screened induced simulator sickness less than one-screened when comparing in the average sickness score. However, the oculomotor were affected simulator sickness from three-screened with parallax 2.0 cm more than one-screened. In addition, it is suggested that a person not wearing head tracking glasses feels more uncomfortable sense in multiple-screened IVE due to scene distortion.

This experiment results suggest to use three-screened IVE with pay attention to set proper parameter conditions.

7.2 Factor effect in simulator sickness in HoloStage™

The environmental factor and human factor effects of simulator sickness are studied. The environmental factors are composed of parallax, number of display screens and subject position while the human factors are age, height difference between driver/passenger and nationality.

The results were analyzed by principal component analysis to determine the significance of each factor effect, according to experiment 2, 3 and 4 results.

Parallax 6.5 cm is suggested for IVE displays. The position effect is the most significant factor correlated with simulator sickness seen in experiment 3 results. In the case of a multiple-screened IVE, people in the passenger positions are more likely than those in the driver position to experience simulator sickness, especially the passengers who stand on the side where the screens join together.

Age factor is the least effective of simulator sickness in IVE, according to the experimental results. However, further research in age effect is recommended to study with larger numbers and wider age range of subjects.

Gender effect does not study in this research because a very less number of female than male subjects. The further research on gender effects on simulator sickness is suggested to use larger and equal numbers of male/female subject with task assign content (e.g. rotational object) to study the difference between male and female.

The safety guidelines in immersive virtual environment are proposed. The immersive virtual environment should be set parallax as 6.5 cm, and set the tallest subject as the driver position (in case of multiple subjects simultaneously enter to IVE), or set the shorter subject as the passenger position. In the other words, bird's eye view is improper for IVE. Moreover, the driver is the best position and we recommend subject to avoid position near several screen connection areas.

7.3 What are these guidelines use for?

Immersive virtual environment currently used in social meaning as

- Virtual Tours (group tour)
  - Museum
    - The study-tour students can pre-study the place by using IVE before the real-tour day.
  - Laboratory, college
  - Medical application
  - The children that are being treated in hospital have to stay only in the hospital. They cannot go anywhere but they can use IVE to enjoy life in 3D outside scene.
- Corroborative work on IVE, e.g. car design, building design. This IVE using will help the team in design-state and save cost.

The IVE can be used for the above purposes. Therefore, the guidelines for experiment in IVE and safety guidelines are important in order to minimize the possibility of simulator sickness in IVE.

These guidelines are obtained from HoloStage™ system. The other multiple-screened IVE, e.g. four-screened CAVE can also use these guidelines by setting tallest person as the driver, set passenger stand close to driver position, passenger should be avoided from screen border connections, or set parallax to 6.5 cm. etc.

7.4 Future works

In future research, the measurement of human physiological parameters of simulator sickness such as ECG, EOG, and body balance during the use of IVE for the analysis of quantitative measurements might be study. Then, this quantitative data will be compared with results found in this present study as self-reported on the simulator sickness questionnaire.

Appendix A

Motion sickness history questionnaire and simulator sickness questionnaire

Date:______________________

Subject #:__________________

The Simulator Sickness Questionnaire and Motion Sickness History Questionnaire are adapted from;

[1] R. S. Kennedy and N. E. Lane : "Simulator Sickness Questionnaire: An Enhanced Method for Quantifying Simulator Sickness", The International Journal of Aviation Psychology, 3(3), pp. 203-220 (1993)

[2] M.J. Griffin and H.V.C. Howarth : "Motion Sickness History Questionnaire", ISVR Technical Report No. 283, May (2000)

Motion Sickness History Questionnaire

1. Age ____________________ year olds
2. Gender ○ Male ○ Female
3. Do you have any medical condition involving the heart or circulation?

   ○ Yes ○ No

   If yes, what is the nature of condition?:

   ____

   Major symptoms :____
4. From the experience, how often do you get carsick?

   ○ Always ○ Frequency ○ Sometime ○ Rarely ○ Never
5. If you were in an experiment where 50% of the subjects get sick, what do you think your chances of getting sick would be?

   ○ Certainly ○ Probably ○ Not sure ○ Probably not ○ Certainly not

Simulator Sickness Questionnaire（酔い度合い）アンケート
Part I: Pre-test assessment

1. Gender ○ Male ○ Female Age ____________years Height __________cm
2. Education level ○ Bachelor ○ Master ○ Doctor ○ Others
3. Have you ever experienced with HoloStage system? ○ Yes ○ No
   If "Yes", your experiences are ○ a few times ○ around 10 times ○ many times
4. Have you been ill in the last week? ○ Yes ○ No
   If "Yes", please provide the information about nature and length of illness:
   ____
   Are you fully recovered? ○ Yes ○ No
5. How many hours sleep did you get last night? ___________ hours
6. Please list any other comment regarding your present physical state which might affect your performance. ____

■次の中から最もあてはまる所に○をつけて下さい。

(Please circle ○ the most appropriate score according to your feeling.)

質問(Question)	**答え(Answer)**			
	なし No	ややある Slight	ある Moderate	かなりある Severe
一般的な不快感（General discomfort)	0	1	2	3
疲労感がある（Fatigue)	0	1	2	3
頭痛がする（Headache)	0	1	2	3
眼が疲れている（Eyestrain)	0	1	2	3
眼の焦点がぼける（Difficulty focusing)	0	1	2	3
唾液の増加（Increased salivation)	0	1	2	3
発汗する（Sweating)	0	1	2	3
吐き気がする（Nausea)	0	1	2	3
集中できない（Difficulty concentrating)	0	1	2	3
頭が重い（Fullness of head)	0	1	2	3
眼がかすむ（Blurred vision)	0	1	2	3
眩暈感がある[開眼] (Dizzy (eyes open))	0	1	2	3
眩暈感がある[閉眼] (Dizzy (eyes closed))	0	1	2	3
周囲が回転する眩暈 (Vertigo)	0	1	2	3
胃の存在感がある (Stomach awareness)	0	1	2	3
げっぷが出る（Burping)	0	1	2	3

***************** STOP HERE *****************

Part II: Post-test assessment

1. Position in HoloStage ○ Left ○ Center ○ Right
2. Parallax setting ○ 2.0 cm ○ 6.5 cm ○ 9.0 cm

■次の中から最もあてはまる所に○をつけて下さい。

(Please circle ○ the most appropriate score according to your feeling.)

質問(Question)	答え(Answer)			
	なし No	ややある Slight	ある Moderate	かなりある Severe
一般的な不快感 (General discomfort)	0	1	2	3
疲労感がある (Fatigue)	0	1	2	3
頭痛がする (Headache)	0	1	2	3
眼が疲れている (Eyestrain)	0	1	2	3
眼の焦点がぼける (Difficulty focusing)	0	1	2	3
唾液の増加 (Increased salivation)	0	1	2	3
発汗する (Sweating)	0	1	2	3
吐き気がする (Nausea)	0	1	2	3
集中できない (Difficulty concentrating)	0	1	2	3
頭が重い (Fullness of head)	0	1	2	3
眼がかすむ (Blurred vision)	0	1	2	3
眩暈感がある[開眼] (Dizzy (eyes open))	0	1	2	3
眩暈感がある[閉眼] (Dizzy (eyes closed))	0	1	2	3
周囲が回転する眩暈 (Vertigo)	0	1	2	3
胃の存在感がある (Stomach awareness)	0	1	2	3
げっぷが出る (Burping)	0	1	2	3

3. If you have some sickness symptom, do you think from what reason?

____

____

4. Please describe any unusual events that occurred during the experiment.

____

____

5. Please describe any problem that you observed in the animation?

____

____

6. Do you have any comments?

____

____

Appendix B

Informed consent form

Graduate School of Science and Technology, Course of Science and Technology, Tokai University

Title of research : Study on Difference of Virtual Sickness between Single-Screen and Immersive Virtual Environment and Proposal for Safety Virtual Contents

Researcher : Chompoonuch Jinjakam

I. The purpose of this research

The purpose of this research is to study the factor effect to simulator sickness in immersive virtual environment by using HoloStage™ system. Then propose the safety virtual display in IVE.

II. The content

The content animation composed of a walk-through road, house, bridge, space area and high building all in common colors for 5 minutes long. All buildings were fixed, but one car object moved. No audio effect occurs in our virtual environment.

III. Risk and freedom to withdraw

There is some risk to you in the study. The content in the experiment is no inherent danger, no horror or unpleasant experiences, or emotional distress. However, different individuals may experience motion sickness-like side effect, e.g. dizziness, nausea, or general discomfort etc. You have right to withdraw anytime during the study when they feel any unpleasant sickness.

IV. Subject's permission

I have read and understand the inform consent and condition of this research. I hereby acknowledge the above and give my voluntary consent to participate in this research. I may withdraw anytime without penalty.

____________________________ ________________________

Signature Date

If you have any questions about this research, please contact:

Chompoonuch Jinjakam

Researcher

Email : chompoonuch@live.kmitl.ac.th, Tel. (080)3342-7800

Appendix C

Miscellaneous

C.1 The luminous intensity

The luminous flux, which is also a photometric quantity, represents the light power of a source as perceived by the human eye. The unit of luminous flux is the lumen (lm). The illuminance is the luminous flux incident per unit area. The illuminance measured in lux (lux = lm/m2).

Table C.1 Typical illuminance in different environments [1].

illumination condition	**illuminance**
Full moon	1 lux
Street lighting	10 lux
Home lighting	30 to 300 lux
Office desk lighting	100 to 1,000 lux
Surgery lighting	10,000 lux
Direct sunlight	100,000 lux

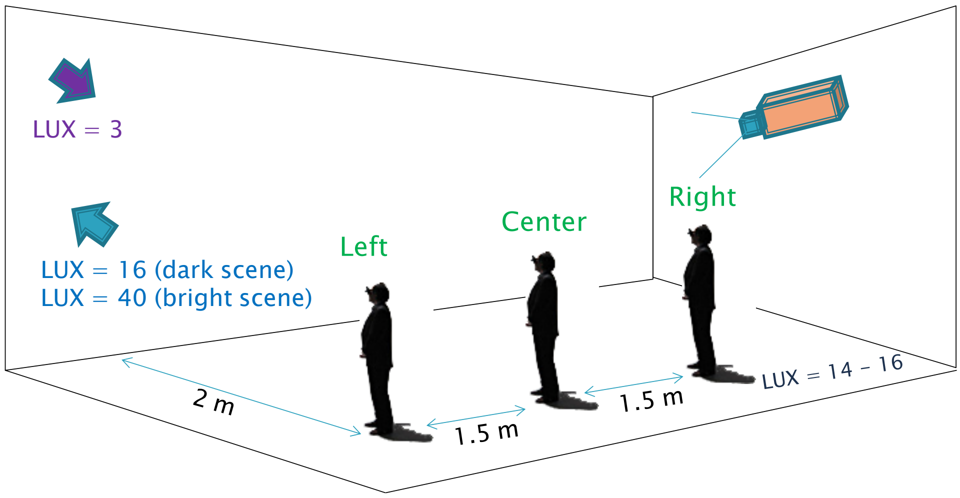

Figure C.1 Luminous intensity from Experiment 3.

Figure C.1 shows brightness from scene in Experiment 3. The most brightness is 40 Lux, that means it is only similar with home lighting. Therefore, even this brightness is more than the scene in Experiment 2 but very low Lux and should not be affected with simulator sickness.

C.2 Center of gravity and toppling rate [2]

- As gravity acts on all parts of the body, one's entire weight can be considered as concentrated at a point where the gravitational pull on one side of the body is equal to the pull on the other side. This point is the body's center of gravity, and it constitutes the exact center of body mass.
- A tall person falls harder than a short person. For the same reason, the further the body's center of gravity is displaced from the midline of its base of support, the more force is necessary to return it to the balanced position.

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