Use of an Independent Visual Background to Alleviate Simulator Sickness in the Virtual Environments that Employ Wide−Field Displays

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Abstract

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Simulator sickness (or so−called Cybersickness) has been a significant problem since the development of virtual reality systems. Numerous studies have investigated this problem. However, there is currently no accepted solution. This dissertation addresses development of a possible approach to alleviate simulator sickness. Prior work has suggested the method of inserting an inertially−matched reference visual background grid into a visual scene as an intervention against simulator sickness, but little work has been done to evaluate or optimize such method. This dissertation describes a series of human factors studies to examine and optimize such an “independent visual background” (IVB). Four major components are included. The first part provides a background regarding simulator sickness. The second part examines the dynamics of sensory conflict theory which has been widely accepted as a model of simulator sickness. In this regard we identified and verified a motion frequency where the summed response from the visual and inertial self−motion systems was greatest. We also investigated the effects of field−of−view of the display. The third part explores the possible characteristics of the IVB including spatial, polarity, temporal and stereographic properties of the visual display. As a means of determining subjects’ reactions to moving visual stimuli, postural stability, was measured. Postural stability has been proposed as an objective measurement for simulator sickness. The fourth part explores ways that the IVB may reduce subjects’ simulator sickness symptoms during the virtual environment exposure. We also consider the relationship between sense of presence and simulator sickness. We conclude that the IVB could be a useful procedure to alleviate simulator sickness and recommend future

experiments regarding how the IVB should be presented to enhance users' task performance and cognitive function.

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Abbreviations

E2i: Engagement, Enjoyment index questionnaire
FOV: Field−of−view
HITL: Human Interface Technology Laboratory
HMD: Head−mounted display
Hz: Hertz
SS: Simulator sickness
SSQ: Simulator sickness questionnaire
UW: University of Washington
VE: Virtual environment
VR: Virtual reality
IVB: Independent visual background

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For me, this is not the end, just another new start!

Dedication

To my parents,

Chapter 1. Introduction

Virtual reality (VR) / virtual environment (VE) technology has been under development for over 30 years and was an especially ‘hot’ research topic during the 1990s. Hundreds of applications employing these technologies can be found in clinical treatment, military training, education, manufacturing, etc. VR was seen as a way of exposing people to immersive 3D environments that afforded natural and intuitive coupling of sensory and psychomotor functions at a fraction of the cost of conventional simulators. Despite the attractiveness of these innovative and advanced interfaces, some people were affected adversely by exposure to these synthetic environments. One of these effects was akin to motion sickness or simulator sickness (SS) / VE sickness, or so−called cybersickness (Stanney and Salvendy, 1998; McCauley and Sharkey, 1992). Unfortunately, procedures to alleviate SS / VE sickness have been of limited value (LaViola Jr, 2000). Stanney and Salvendy (1998) posed important questions related to SS / VE sickness that require answers: how can aftereffects be characterized? How should they be measured and managed? How can prolonged exposure to VE systems be obtained and what are the effects on task performance? This dissertation investigates the dynamics of SS to discover the possible ways to predict the incidence of SS / VE sickness, and then, following the ‘rest frame hypothesis’ proposed by Prothero (1998), attempts to develop and explore effective ways to alleviate simulator sickness. The dissertation includes three parts. The first part reviews the literature and relevant theories. The second part discusses the dynamics of sensory conflict theory, which is the widely accepted explanation of SS / VE sickness. This section includes consideration of the frequency cross−over response and the effects of field−of−view (FOV) in an immersive environment. The third part explores the characteristics of an intervention – the independent visual background (IVB). The discussion concludes with recommendations for future research.

Chapter 2. Simulator Sickness

2.1 Introduction

SS is expected to become increasingly troublesome as VE technology evolves (Stanney and Salvendy, 1998). As technology evolves to produce more realistic, compelling graphics, the problem of SS / VE sickness is expected to be exacerbated. The topic of SS / VE sickness also appears periodically on game sites and message boards. Interestingly, it is seldom addressed by the game industry (Howard, 2000). Some game developers have proposed a number of solutions; but many are contradictory. For example, some gamers decrease the picture resolution to increase frame rate while others try to increase the picture resolution to get better picture quality, because they think unrealistic−looking graphics is a cause of SS. In this section, we will discuss characteristics, measurements, and theories of SS.

2.2 Characteristics of Simulator Sickness

The symptoms of SS/ VE sickness are similar to motion sickness. There is a wide variety of simulator sickness symptoms that people report. Different people have different susceptibilities to SS. Common effects of simulator sickness include nausea, dizziness, sweating, disorientation and so on (see Table 2−1). Kennedy and Stanney (1997) analyzed eight different VE experiments whih using three different VEs presented on HMDs. They found that for VEs the relative magnitudes of symptom clusters were disorientation > nausea > oculomotor, whereas the relative magnitudes for flight simulator were oculomotor > nausea > disorientation. According to Regan and Price’s (1994) study, the incidence rates of SS were 61 %. Out of 146 subjects, 89 subjects reported SS symptoms at some point during a 30 min post−exposure period in a flight simulator. Kennedy and Stanney (1997) found similar results. They found the incidence levels in early VE studies to be so high that only 5% to 10 % of users reported no symptoms. They also concluded that VE users report more sickness than flight simulator users and astronauts during space travel.

Several factors determine susceptibility to simulator sickness including individual differences, task factors and simulator factors. Identifying those factors is critical to reducing SS. Stanney and Salvendy (1998) suggest that the potential factors fall into three categories: human characteristics, VR display characteristics and task characteristics (see Table 2−2).

Table 2−1 Aftereffects of simulator sickness

Visual	Mental	Somatic
Blurred vision	Disorientation	Salivation
Eye strain	Dizziness	Sweaty palms
Difficulty focusing	Discomfort	Stomach awareness
	Fatigue	Nausea

The relationships between incidence, severity of motion sickness, and motion stimulus variables including frequency, magnitude, direction and duration have been addressed in numerous studies (Griffin, 1990). Because it is thought to be a prime cause of motion sickness in some ships, vertical oscillation has been extensively studied. For example, Lawther and Griffin (1987) found the highest incidence of vomiting during vertical oscillation at 0.03 to 0.5 Hz. The British Standard (1987) for vertical motion combines data from several studies and indicates that the motion sickness response peaks at about 0.2 Hz and falls off at frequencies above and below this value. Horizontal oscillation has also been addressed in several studies. Recently Golding, Finch and Stott (1997) reported that motion sickness decreased with increasing frequency above 0.35 Hz (the lowest frequency tested). However, the slope of the frequency by sickness curve was less steep than expected based on vertical oscillation data (*).

Table 2−2 Factors to contribute simulator sickness

Human characteristics	VR display characteristics	Task characteristics
Age	Color	Degree of control
Concentration	Contrast	Duration
Race	Field−of−View	Head movement
Experience (in real world)	Motion platform	Sitting or Standing
Experience (in simulator)	Resolution	
Gender	Frame rate	
Expectation	Luminance	
Motion sick history	Dynamic range	

* British Standards Institution. Measurement and evaluation of human response to whole−body mechanical vibration and repeated shock, BS 6841. London: British Standards Institution, 1987.

2.3 Theories of Simulator Sickness

The exact causes of simulator sickness are not thoroughly understood (McCauley and Sharekey, 1992). The phenomenon of SS/ VE sickness is similar to motion sickness. Both simulator and VE sickness are thought to be caused, in part, by the same conditions that result in motion sickness. A well−known and widely accepted approach to explain these phenomena is the sensory conflict theory (Griffin, 1990, Reason, 1978, Reason and Brand, 1975). This theory suggests that simulator sickness arises from conflicts between the visual and inertial orientation and motion cues. Spatial orientation and perception of self−motion derive from visual and vestibular signals. (The vestibular receptors within the inner ear include 3 angular and 2 linear accelerometers / tilt detectors in each ear.) Following the sensory conflict theory, VR systems may provide visual motion cues, but no corresponding vestibular cues. Thus, cue conflicts may develop. If one is in a visual environment that evokes a strong feeling that one is moving, such as an IMAX theater, while the body is, in fact, stationary, one may experience SS. The sensory conflict theory provides one explanation for the occurrence of SS/ VE sickness. However, several investigators have noted problems with this theory (Stoffregen, Hettinger, Hass, Roe and Smart, 2000; LaViola Jr, 2000; Stoffregen and Riccio, 1991). It seems that sensory conflict does not reliably predict the severity of SS / VE sickness and which makes it difficult to develop interventions to alleviate SS / VE sickness.

As an alternative to the traditional sensory conflict approach, Riccio and Stoffregen (1991) proposed a “postural instability theory” to explain SS. Based on an ecological psychology perspective, they suggested that maintenance of postural stability is one of the major goals of animals. Animals tend to become sick in circumstances where they have not learned strategies to maintain their balance. Riccio and Stoffregen suggest that people in a simulator need to learn new ‘patterns’ to control their postural stability. Until this learning is complete, these people may experience SS. Recent data reported by Stoffregen, Hettinger, Haas and Smart (2000) and Stoffregen and Smart (1998) support this postural instability theory.

2.4 Self−motion Systems

Hettinger, Berbaum, Kennedy, Dunlap and Nolan (1990) have shown that vection, visually induced self−motion perception, is required for SS to occur. Perception of self−motion is mediated primarily by the visual and vestibular systems. Through their encounters with waterfalls and similar phenomena, early humans must have recognized that visual scene motion can evoke illusions of self−motion and self−orientation as well as postural disturbances and reflexive eye movements. Nearly everyone who drives a car reports that while waiting at a stop light they have braked sharply, only to realize that they were not moving; rather, the forward creep of an adjacent car evoked the illusion of backward motion. Similar phenomena were common in large, multi−track railroad stations in an earlier time.

Disturbances and illusions evoked by visual motion have been examined in numerous studies. Much of the earlier work has been reviewed by Dichgans and Brandt (1978) and Howard (1986). Subsequent research has addressed issues such as the region of the visual field most likely to evoke disturbance and the role of visual background versus foreground.

Observers placed inside a rotating optokinetic drum initially report that the drum is moving and that they are stationary. After periods of several seconds, observers report that they are moving and the drum is stationary. Latency of self−motion onset depends on numerous factors including visual scene velocity (Dichgans and Brandt, 1978; Wong and Frost, 1978). Self−motion can be evoked by constant velocity visual stimuli for periods ranging from minutes to hours, although “drop−outs” occasionally are reported. This illusory self−motion is the basis for many types of motion simulators (see Rolfe and Staples, 1986) as well as amusement park rides and games. The visual self−motion system can be described as a low−pass frequency filter. Effects associated with manipulation of visual motion frequency have been summarized by Berthoz, Lacour, Soechting and Vidal (1979). (See Figure. 3−4, Berthoz’s data).

Inertial physical motion is sensed by the vestibular receptors in the inner ear. The semicircular canals, which can be modeled as integrating angular accelerometers, respond to rotational motion around the pitch, roll and yaw body axes. Translational motion as well as tilt with respect to gravity are sensed by the otolith receptors, which can be modeled as linear accelerometers. Vestibular receptors help control eye movements and posture and contribute to perception of self− orientation and self−motion.

Responses of the semicircular canals and the otolith receptors have been characterized in numerous studies (Grant and Best, 1987; Howard, 1986; Wilson and Melvill Jones, 1979). As for all biomechanical systems, output from the vestibular receptors varies with stimulus frequency. Because they behave as accelerometers, the vestibular receptors do not respond to constant velocity (“DC”) motion. (Gravity can be described as a linear acceleration; therefore, the otolith receptors do respond continuously to sustained head tilt with respect to gravity.) Because they have mass components, there is an upper limit to the input frequencies that will evoke response from the vestibular receptors. Consequently, the receptors behave as band−pass frequency filters. Melvill Jones and Milsum (1965) summarized data from several experiments which indicate that the frequency range over which semicircular canal receptor responses exhibit unity gain (output equal input) is 0.1 – 5.0 Hz. However, for the stimulus frequencies used in the present dissertation, the semicircular canals may be described as high−pass frequency filters.

2.5 The Role of FOV / Resolution on Simulator Sickness

Effects of image quality variables such as FOV and resolution on SS have been examined by several investigators. Stanney and Salvendy (1998) proposed that FOV and display resolution may affect the usability of a display system and may correlate to motion sickness. Observers usually report higher incidence of SS with a wide FOV display than with a narrow FOV (Kennedy, Lilienthal, Berbaum, Berbaum, and McCauley, 1989). A wide FOV display provide greater stimulation to the peripheral retina leading to a feeling of immersion of the user in the virtual environment. Narrow FOVs may degrade the sense of presence (Prothero and Hoffman, 1995; Hettinger, Nolan, Kennedy, Berbaum, Schnitius and Edinger, 1987). DiZio and Lackner (1997) evaluated 21 subjects in two different FOV conditions. Subjects reported more motion sickness symptoms during 15 min exposures when using a wide FOV head−mounted−display (HMD) (138º horizontal by 110º vertical) than when they were exposed to a FOV half as large.

FOV may also influence spatial awareness in VEs. Witmar, Bailely, & Knerr (1994) reported that when subjects moved through a VE, the limited FOV could cause frequent collisions with walls and doorways. Subjects apparently failed to detect VE features such as intersections between the walls and floor, etc. Kline and Witmer (1996) found that distance estimates were also affected by

FOV. They tested 12 different viewing distances in a VE (1−12 feet). Subjects overestimated distances when presented with a narrow FOV (60º X 38.5º) and underestimated the same distances with a wide FOV (140º X 90º). Limited FOV interfered with development of spatial knowledge and increased navigational difficulties (Alfano and Michel, 1990). McCreary and Williges (1998) reported that when using an HMD, larger FOVs resulted in greater route and configuration knowledge while landmark knowledge was not significantly changed. Kenyon and Kneller (1993) examined a visual nulling task at five different FOVs (10º, 20º, 40º, 80º and 120º). They found that subjects' minimum RMS error occurred at the 80º FOV, not 120º FOV. Also subjects reported task difficulty greater at the 120º FOV than at the 80º. They suggested that subjects experienced stronger vection at this FOV, making the nulling task more difficult. Because large FOVs cover most of the peripheral regions of the retina, they may more effectively produce self−motion perception (Hettinger et al., 1987).

Determining the region of the retina most responsible for the perception of self−motion has been addressed by many researchers (see Wolpert, 1990). Initial reports indicated that stimulation of the peripheral areas of the retina was more effective in eliciting perception of self−motion than stimulation of more central areas (Dichgans & Brandt, 1978; Held, Dichgans, & Bauer, 1975).

These experiments led scientists to theorize that human vision is mediated by two functionally different systems. Leibowitz and Post (1982) extended the notion of "two modes of processing spatially distributed information" which was proposed by Held (1970) and others. The two modes of spatial processing described two different kinds of visual functions associated with different parts of the brain. One is the focal mode and the other is the ambient mode. The former was thought to be responsible for object recognition and identification and concerned with the 'what' question. The latter was thought to be responsible for spatial orientation, locomotion and posture and concerned with the 'where' question.

Several studies examined this theory. Brandt, Dichgans, and Koenig (1973) found that when the central retina was stimulated, self−motion was not experienced, but strong self−rotation was elicited when the peripheral retina was exposed to optical flow. Hulk and Rempt (1983) using sine−wave gratings of various widths, found that self−motion was most frequently reported at FOV eccentricities of 50º and 60º with the slower angular velocities 10º/sec − 15º/sec proving most effective. Howard and Heckmann (1989) reported that when stimuli were presented in the peripheral visual field, self−motion experienced by the subject was stronger than when the stimuli were presented in the central visual field. However, vection was reduced when the central stimuli moved opposite the direction of the peripheral stimuli. Howard , Ohmi, Simpson, and Landolt (1987) studied the interaction between central−peripheral and far−near placement of two displays in generating circular−vection. They found that strong vection could be evoked by a centrally located moving pattern if that pattern was perceived as being more distant than a stationary surround. Vection appears to be strongly related to perceptual distinction between foreground and background.

Warren and Kurtz (1992) reviewed several experiments that contradicted Brandt’s et al. (1973) peripheral dominance hypothesis – that peripheral vision is specialized for self−motion perception. Based on studies of perceived heading accuracy, Warren and Kurtz found that the periphery is less sensitive to radial optical flow than the central region. Even FOVs as small as 10°−25° evoked self−motion perception. Stoffregen (1985) reported that postural adjustments were evoked by either radial or parallel (lamellar) optical flow in the central visual field but only by lamellar flow in the periphery. Anderson and Braunstein (1985) found that with the displays subtending angle as small as 7.5°, subjects still reported vection and motion sickness. They suggested that the veridical representation of motion in depth might be the critical element in perceiving self−motion.

Pausch, Crea and Conway (1992) suggested that display FOV is one of several factors that may contribute to SS. Higher picture resolution and quality may allow more information be to presented in particular display areas. Higher resolution permits increased scene information and ‘realism.’ Welch, Blackmon, Liu, Mellers and Stark (1996) found that pictorial realism correlated with perceived sense of ‘presence’ a VE. However, it is difficult to evaluate effects of resolution and realism because of possible interactions with other display characteristics such as FOV.

Ziefle (1998) investigated effects of 3 different resolutions, using a cathode−ray−tube (CRT) display, on eye movements during a visual search task. Reaction times and fixation durations were increased in the low−resolution condition (62 dpi, 720 X 540 pixels) as compared with high−resolution (89 dpi, 1024 X 768 pixels) by 19% and 9.6% respectively. Gould, Alfaro, Finn, Haupt and Minuto (1987) found that the higher the resolution of the display, the better the reading performance. Kline and Witmer (1996) studied effects of 3 texture resolutions (512 X 512 pixels, 16 X 16 pixels and no texture) and 2 texture types (rich, emergent and poor, non−emergent) on distance estimates. They found that fine texture resolution improved the accuracy of estimates for distances fewer than 6 feet when using a narrow FOV. They suggested that higher texture resolution might improve depth perception and distance estimation in a narrow FOV VE system. However, Watson, Walker, Hodegs and Worden (1997) investigated the relationship between visual search performance and resolution. They found that degrading visual complexity in the periphery did not significantly reduce performance.

2.6 Rest Frame Hypothesis

Prothero, Draper, Furness, Parker and Wells (1999) suggested that SS doesn't derive from conflicting motion cues per se but rather from conflicting rest frames implied by those cues. Their proposed 'rest frame hypothesis' derives from the observation that humans have a strong perception that some things are stationary. Humans tend to select certain things that are stationary to minimize mental calculations. This "rest frame hypothesis" suggests a procedure which uses visual background manipulation for alleviating simulator and VE sickness. The visual display presented in a VE can be divided into two components, one representing the "content" of the VE and the other matched to the observer's physical inertial environment. The latter may be labeled the IVB. If the reference frames implied by the IVB and the observer's inertial receptors are congruent, selection of a single rest frame should be easily accomplished and incidence of simulator / VE sickness should be reduced.

Prothero and his colleagues presented a circular vection stimulus that rotated in the yaw direction. It was shown for 3 to 4.5 min on a head−mounted−display (Virtual i/O i− glasses!, FOV 30º by 24º) that could be used either in the occluded or see−through mode. The vection stimulus appeared on a semi−transparent surface. For the IVB condition, the stationary laboratory wall was visible behind the stimulus. For the non−IVB condition, a mask was placed behind the display surface so the subject could not see the laboratory wall. In another experiment, they used a visual task to force the subject's attention to the visual foreground. They found in both experiments that subjects exhibited less postural disturbance and reported fewer SS symptoms in conditions where they could see laboratory wall behind the see−through goggles on which a moving scene was displayed (IVB condition) than when the goggles were occluded (no−IVB condition).

Design of an IVB to alleviate simulator and VE sickness analogous to the laboratory walls in Prothero's experiment requires answers to several questions including the following: what are appropriate characteristics for an IVB? Can it be a simple grid? How noticeable must the IVB be relative to scene content? Where should it be located (peripherally versus centrally) in the visual field? Does it interfere with processing or enjoyment of VE scene content?

2.7 Measurement of Simulator Sickness

Based on work on sea and space sickness, there are several different ways to measure simulator sickness. One is subjective self−report of somatic conditions after exposure. Another is objective measurement of physiological responses evoked by stimulation of the vestibular, visual and proprioceptive systems.

The most commonly used subjective assessment tool is the Simulator Sickness Questionnaire (SSQ). It was originally devised to evaluate aircraft simulator systems (Kennedy, Lane, Berbaum and Lilienthal, 1993). SSQ lists 16 symptoms, which are rated by the subject on a 4−point scale. There are 3 subscales in this questionnaire: Nausea – general discomfort, sweating, nausea etc; Oculomotor – eyestrain, difficulty focusing, blurred vision etc; Disorientation – difficulty focusing, dizziness, vertigo. Kennedy et al. (1993) pointed out that subscale scores can provide diagnostic information as to the specific causes of the resulting sickness.

In addition to the subjective assessment tools, there are several objective assessment methods. Postural testing is one of them. Kennedy and Stanney (1996) have evaluated postural stability measures for assessing aftereffects from virtual environment exposure. They suggested that postural stability could be used to rate, and potentially to certify, levels of expected disturbance from different VE systems. Several studies indicate that balance disturbance correlates highly with SS, and that balance disturbance may be considered a surrogate for simulator sickness intensity. Cobb and Nichols (1998) examined 40 subjects who were exposed to 20 min of immersion in an interactive virtual environment, with restricted user movement. They found that balance disturbances were strongly correlated with simulator sickness. Hamilton, Kantor and Magee (1989) reported similar results. Dizio and Lackner (1997) found a five fold increase in sway amplitude after 15 min of VE exposure relative to pre−exposure using a Kistler force platform and the standard Romberg posture. Recently Stoffregen et al. (2000) reported that head instability was significantly greater for subjects who subsequently became motion sick than for those who did not become sick.

Vestibulo−ocular reflex (VOR) changes have also been suggested as possible predictors of susceptibility to SS during VE exposure (Draper, 1998). In addition, Stanney, Kennedy, Drexler and Harm (1999) have developed a means of measuring changes in the kinesthetic position sense due to virtual environment exposure. Changes in EEG, salivary cortisol composition, heart rate levels and variability have also been used as objective measurements after exposure in VEs (Ramsey & Wilson, 1998). Table 2−3 shows the relevant research.

Table 2−3 Measurements of simulator sickness

Subjective	Objective
SSQ (Kennedy et al., 1993)	Postural equilibrium (Cobb, 1999; Kennedy and Stanney, 1996)
SS checklist (Cobb, 1999)	VOR adaptation (Draper, 1998)
	Proprioceptive perception (Stanney et al., 1999)
	Other physiological symptoms

Although our ultimate purpose is to address SS in this dissertation, Part I and Part II experiments examined effects on balance. Reasons for using balance disturbance as the dependent variable include the following: First, as described above, research shows that balance disturbance has been suggested as a surrogate measure for simulator sickness intensity. Also postural disturbance has been proposed for evaluating VE systems (Stanney and Salvendy, 1998). Second, it is much easier to recruit subjects for an experiment on balance performance, which has few aftereffects, than for one on motion sickness, which often has substantial aftereffects. Consequently, this dissertation selected SSQ as subjective and postural stability as objective measurements.

2.8. Mitigation of SS / VE Sickness

Since the exact causes of simulator sickness are not thoroughly understood, it is difficult to apply a specific method to reduce simulator sickness. Even if we make a perfect virtual reality display, our eyes still may see a world that is moving in ways the body knows it is not. However, researchers have proposed several ways to alleviate simulator sickness. Dizio and Lackner (1997) proposed a method for alleviating motion sickness for an HMD−based virtual reality system. During head movements, if we can 'grey out' or blank the display above a threshold level of head velocity, the effect of visual update delays may be eliminated. Warren & Hannon (1998) suggested that reducing the spatial frequency content of the display and degrading the optic flow may reduce simulator sickness. Prothero (1998) proposed the 'rest frame hypothesis' as described in Section 2.6. He stated that if we can provide an "independent visual background" in the virtual environment so as to offer a rest frame, it may be a way to reduce simulator sickness.

Several additional procedures to mitigate SS have been proposed. Based on the observation that ocean and space travelers report reduced disturbance over time, sensory−motor adaptation is one of these. Kennedy and Fowlkes (1990) reported that subjects' symptoms of SS decreased with repeated VE exposures. Parker and Harm (1992) proposed that training operators to improve their mental rotation performance may increase their ability to adapt to the stimulus rearrangements produced by VEs. However, a problem with adaptation is that when VE−adapted subjects return to the normal world, they often experience re−adaptation disturbance. Postural control, hand−eye coordination and so on need re−adjustment. Anti−motion sickness drugs and biofeedback training also have been proposed to prevent SS symptoms. In the recent study, Stoffregen et al. (2000) proposed some suggestions for design and use of flight simulators. They suggested that on−line monitoring of users' postural control might be used to prevent sickness while allowing uninterrupted use of the system. However, these seem less applicable for casual, recreational use of VE.

2.9 Association between Simulator Sickness and Presence

The sense of 'presence' is one of the important factors for virtual environment design. Presence has been defined as the degree to which participants feel that they are somewhere other than where they are physically located when they experience the effects of a computer−generated simulator (see Bystrom, Barfield and Hendrix, 1999). Witmar and Singer (1998) defined presence as the subjective experience of being in one place or environment, even when one is physically situated in another. Although this topic has been widely discussed, there is no common agreement for the definition of presence (Stanney and Salvendy, 1998). Lack of an accepted definition affects the development and usage of presence measurements (see Witmer and Singer, 1998; Slater, 1999; Singer and Witmer, 1999; Usoh et al., 2000).

Although there is no consensus regarding the definition of presence, researchers still try to develop methods to measure presence. Some subjective measurements have been suggested including rating scales, the method of paired comparisons, cross−modality matching (see Stanney and Salvendy, 1998) and analysis of essays written about the experience (Slater and Usoh, 1993). The Presence Questionnaire developed by Witmer and Singer (1998) and questionnaire developed by Slater et al. (1998) and Usoh et al. (1999) are widely used. Some objective measurements also have been used for evaluating presence such as physiological measurements. Stanney and Salvendy (1998) suggested that a problem for objective measurement is that the relation to presence may not be clear. For example, sweating may vary with the air conditioning in the experiment room rather than the exposure of virtual environment.

Since the value of subjective measurement has been debated, some researchers are looking for better measurements. Task performance has been proposed as a good criteria for presence. One reason is that users who did better in a VE usually reported they had high presence (Welch, 1999). Nash, Edwards, Thompson and Barfield (2000) summarized performance metrics which have been used for accessing presence. However, the question remains, does the high presence contribute to high task performance? Welch (1999) suggested that it is very difficult to determine whether the relationship between task performance and presence is casual or correlational. It will depend on conducting unconfounded studies and identifying mediating variables. Nash et al. (2000) noted that the limiting or decreasing information available to the user in the VE may be different from similar limiting in the real world, which could result in lower presence and performance in the VE.

What is the relationship between SS and presence? There is no generally accepted conclusion regarding this relationship. Some studies showed that they are positively correlated; other studies reported a negative correlation (see Stanney and Salvendy, 1998). Are there only two possible relationships? Maybe not. We know that users' experienced of SS varied with VE systems characteristics. Further, it is likely that the relationship between SS and presence also varies across time. Stanney and Salvendy (1998) suggested that both SS and presence may correlated with intervening variables such as vection. Wilson, Nichols and Haldane (1998) noted that enjoyment is one of the important variables correlated with presence.

2.10. Structure of Experiments

The dissertation describes a series of human factors studies to investigate the effects of VE characteristics and wide FOV displays on SS, to explore possible procedures to alleviate SS, to attempt development of a surrogate SS measurement and to estimate the relationship between SS and presence. It includes 3 parts (see Figure 2−1).

The first part addresses the dynamics of SS. The experiments we conducted were designed to refine the sensory conflict theory. While horizontal and vertical oscillation have been examined in numerous studies, we are unaware of studies that have addressed the motion sickness frequency response as a function of oscillation around the yaw axis in an upright observer. We tried to determine the effects of the frequency responses of our visual and inertial self−motion systems and to examine the hypothesis that conflicting visual and inertial motion cues at a "cross−over" frequency would be more likely to elicit sickness than conflicting cues at a higher frequency. Since the characteristics of a wide FOV display are important factors for vection research, we also examined the effects of FOV, scene content, and resolution. The findings from part I, suggest the basic mechanism of sensory conflict theory and the effects of wide FOV display. The second part of the dissertation identifies the effects of an IVB on balance disturbance and evaluated the properties of IVBs designed to reduce disturbances due to VE exposure. We tried to explore the spatial, polarity, temporal and stereographic properties of IVBs. The intent of the IVB research is to identify the possible characteristics of the IVB and to develop effective methods to reduce SS without interfering with a sense of presence and pleasure. The third part of this dissertation verifies the effects of an IVB on SS and explores the relationships among the SS, measurements of presence and the IVB. From the second part of the dissertation, we know that the IVB can reduce postural disturbance evoked by the scene motion, which we thought it might be the precursor of SS. The biggest question is can the IVB reduce SS during VE exposure? Also, we are interested in how the IVB interacts with subject's sense of presence, which is a critical factor for VE interface design.

All three parts are connected by the experimental measurements. In the part I, we try to demonstrate that the postural stability might be a surrogate objective measurement for assessing SS. In the part II, we show that IVBs successfully reduce subjects' postural disturbance during roll axis scene oscillation in a wide FOV display. In the part III, we applied what we learned from parts I and II and then tested the IVB in a real driving simulator. Subjective measurement – the SSQ was used to verify the effect of an IVB.

This dissertation starts from an understanding of SS characteristics and image quality issues in wide FOV displays, and then develops a solution, the IVB, for reducing effects of VE exposure. The dissertation examines characteristics of effective IVBs, verifies IVB effectiveness in a driving simulator, and explores relationships between SS and presence. Following review of previous research, postural stability and SSQ are chosen as objective and subjective measurements for the three parts.

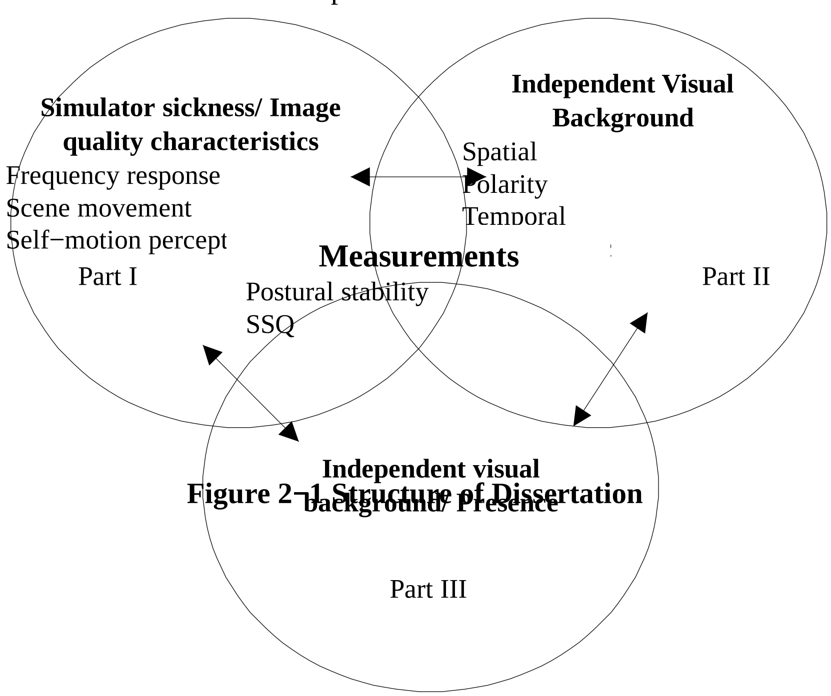


Figure 2–1 Structure of Dissertation

Chapter 3: Part I: The Dynamics of Sensory Conflict Theory

3.1 Introduction

Following the discussion in Chapter 2, we know the causes of SS are not fully understood. In this Chapter we will explore the dynamic characteristics of SS including temporal frequency response, and the effects of FOV, and visual scene resolution. Four sections are in this Chapter. The frequency response experiment includes two studies that examined the frequency response of the visual self−motion system. Based on those results and data from other laboratories, we determined a motion frequency where the summed response of the visual and inertial self−motion systems was maximized. The cross−over frequency range experiment examined the hypothesis that conflicting visual and inertial motion cues at this lower “cross−over” frequency would be more likely to elicit sickness than conflicting cues at a higher frequency. The third section of this Chapter addresses the effects of FOV. We also found different perceptual styles among the people who behaved differently in our experiment. The final experiment examined the effects of FOV and resolution. Ultimately, these studies were intended to form the foundation of a broad effort to develop interventions to alleviate SS.

3.2 Experiment

3.2.1 Frequency Response Experiment

The specific purpose of the frequency response experiments was to determine the effects of frontal roll visual scene oscillation on balance. Our hypothesis is that the visual self−motion perception system response will be greater for lower scene movement frequencies than for higher ones.

3.2.1.1 Method

3.2.1.1.1 Frequency Response Experiment 1

Participants. 3 women and 8 men, ages 23 to 63, were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. Subjects were paid $15 / hour. The protocol was approved by the University of Washington Human Subjects Review Committee.

Apparatus. Visual scene motion was generated by WARP TV (Warp LTD). This procedure uses a table look−up procedure to access a series of digitized video images to simulate scene motion. The scene used was a waterfall on the island of Maui. The images were presented on a VR4 (Virtual Research System Inc.) head−mounted display (HMD) which has a nominal 48° x 36 FOV and 640 x 480 pixel resolution. Subjects stood on a Chattecx balance platform (Chattecx Corp.) that automatically determined dispersion around the center−of−balance based on signals generated by force plates on which the subjects stood. Dispersion is calculated by determining mean center−of−balance (COB) along the X and Y axes. The squared deviations of sampled points from the COBs are used to calculate a standard deviation – the dispersion index.

Procedure. Frontal visual scene roll oscillation was presented at 5 frequencies: 0.8, 0.4, 0.2, 0.1, 0.05 Hz. Peak scene velocity was constant across frequencies at approximately 70°/sec. Data were collected which the subjects with in a sharpened Rhomberg stance i.e., they stood on the balance platform one foot in front the other and with their arms crossed behind their backs. This stance is commonly used in vestibular research (Hamilton et al, 1989). The balance system collects data at a sampling rate of 100 Hz. One subject was unable to maintain the normal sharpened Rhomberg stance; for him the force plates were offset laterally 4 cm.

5 trials (replicates) were collected in each stimulus condition. 10 sec periods of baseline data, eyes closed in darkness, were collected before and after the visual stimulus trials. For the latter, the subjects looked at the moving scene for 10 sec while holding the support bars. This was done to allow the vection response to develop. The subjects then assumed the Rhomberg position, and attempted to stand steady during the 10 sec data collection. The subject’s eyes were closed except during the visual stimulus trials. The order of roll oscillation frequencies was randomized across subjects.

The following data were collected for each trial: stance break (yes, no), latency to stance break (10 sec maximum), subjective difficulty rating (1−10 scale); dispersion of center−of−balance. A stance break occurred when subjects uncrossed their arms or moved their feet off the force plates. Difficulty ratings reflect subjects' perceptions of their difficulty in maintaining steady, upright posture.

3.2.1.1.2 Frequency Response Experiment 2

Experiment 1 was replicated with the following changes. The visual scene was a simple black and white radial pattern, similar to a propeller. This image was back−projected by a Boxlight video projector onto a 36 in diameter coated plastic dome. 9 subjects stood on the balance platform leaning forward so that their heads were in the dome. The FOV was about 180° x 180°. The experiments setting is shown as illustrated in Fig. 3−1. 4 women and 5 men, ages 20 to 30, participated in Experiment 2.

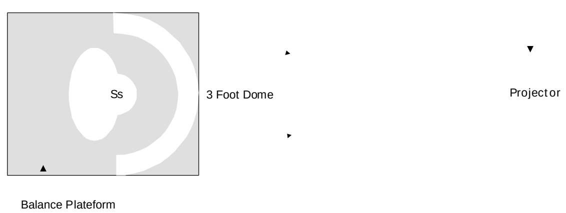
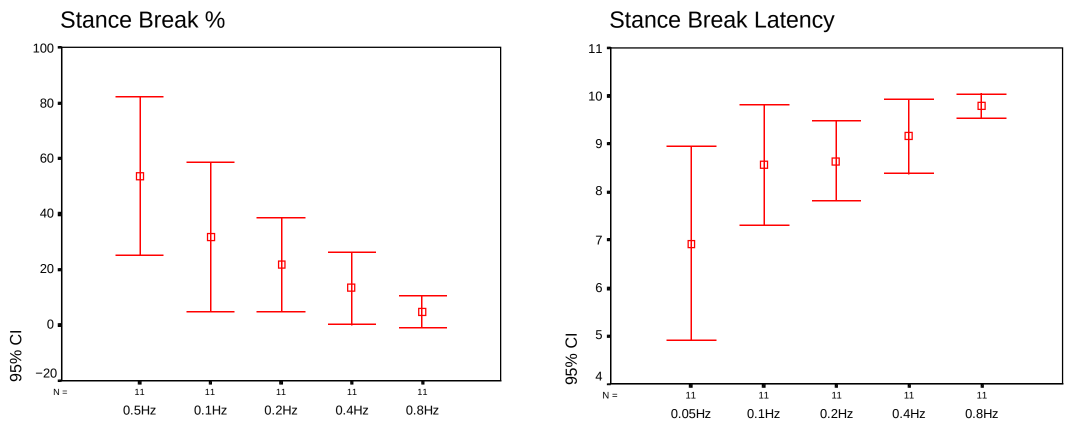


Figure 3−1. Experiment equipment setting

3.2.1.2 Results – Frequency Response Experiment 1 and 2

Because of large inter− and intra−subject variability, difficulty ratings and balance dispersion scores were 'standardized': each visual trial score was divided by the average baseline performance for that subject.

Figure 3−2. Frequency response experiment 1, effects of visual roll oscillation, for all the measures, subjects were least unstable during high frequency – 0.8 Hz roll oscillation and most



unstable during low frequency – 0.5 Hz oscillation

The results from Experiments 1 and 2, illustrated in Figure. 3−2 and 3−3, show that balance disturbance was inversely related to scene oscillation frequency. For all of the measures, the baseline data were essentially equivalent to the highest roll oscillation frequency − 0.8 Hz. For Experiment 1, increasing postural disturbance was recorded with decreasing frequency for difficulty rating (F [4,40]=3.29, p=0.02) and balance dispersion (F [4,40] = 5.34; p = 0.002). Equivalent results were obtained from Experiment 2 for difficulty rating (F [4,32]=3.457, p=0.019) and for balance dispersion (F [4,32]=6.277, p=0.001).

Figure 3−3. Frequency response experiment 2 results of effects of visual roll oscillation.

3.2.1.3 Discussion – Frequency Response Experiments 1 and 2

Clear effects of visual scene motion frequency on balance were observed. The data were essentially equivalent across four dependent variables. The experimental result confirmed our hypothesis that the visual self−motion perception system response will be greater for lower scene movement frequencies than for higher ones. This supports conclusions by Cobb and Nichols (1998) and Hamilton, Kantor and Magee (1989) that the balance measurement procedure can be used in studies to address SS interventions.

High frequency (0.8 Hz) scene motion evoked little or no balance disturbance, which was surprising to most of the subjects. Low frequency motion (0.1 − 0.05 Hz) evoked much greater disturbance. The curves in Figures 3−2, 3−3 suggests that the visual self−motion system frequency response peaks below 0.07 Hz.

Figure 3−4 illustrates balance disturbance as a function of scene motion frequency. Difficulty rating and dispersion data from frequency response experiments 1 and 2 are plotted separately. These 4 data sets are combined in a HITL average curve. Figure 3−4 also illustrates the combined data from three studies that examined subjective sensations of self−motion (vection) elicited by horizontal or vertical linear oscillation summarized by Berthoz et al. (1979). With the exception of the difficulty rating data from frequency response experiment 1, the curves are quite similar.

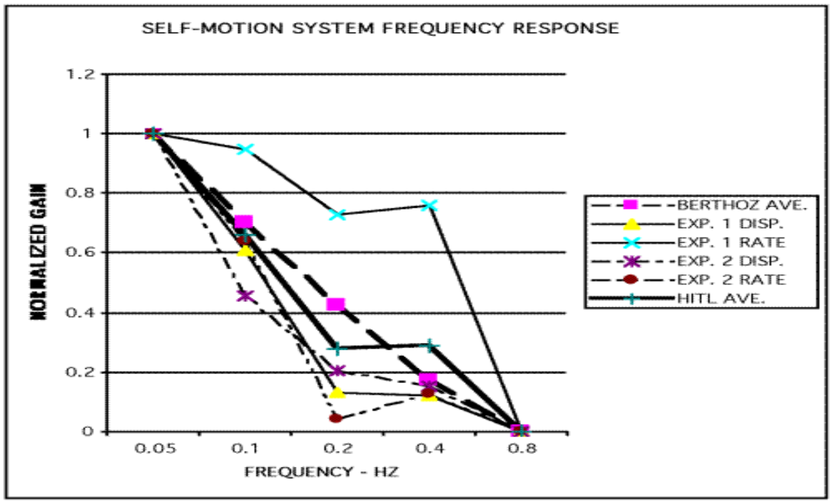


Figure 3−4. Self−motion system frequency response – combined data.

3.2.2 Cross−over / SS Experiment

As illustrated in Figure 3−4, the visual self−motion system exhibits low−pass filter characteristics. In Figure 3−5, data from the studies reported by Berthoz et al. (1979) are combined with the HITL average curve in a single visual self−motion frequency response curve. At frequencies below 5 Hz, the vestibular self−motion system operates as a high−pass filter. Widely cited data from Melvill Jones & Milsum (1965) are also plotted in Figure 3−5. The maximum overlap between the visual and vestibular self−motion systems appears to be around at about 0.07 Hz. Conflicting motion cues at this frequency should evoke SS.

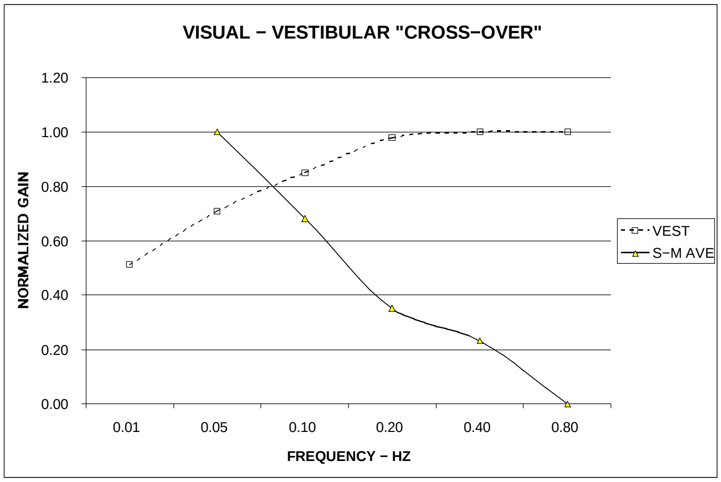


Figure 3−5. Visual−Vestibular Cross−Over. Squares: vestibular response (Melvill Jones & Milsum, 1965). Triangles: visual response −− combined data HITL and Berthoz et al. Maximum overlap appears be about 0.07 Hz.

The curves plotted in Figure 3−5 suggest that the visual self−motion frequency response crosses the vestibular self−motion response at 0.07 Hz; i.e., this is the frequency at which the summed gain from these systems is maximum and therefore has the potential to evoke the greatest conflict. Based on these data and the sensory conflict theory, we hypothesized that simulator sickness was most likely to be evoked by conflicting motion at the cross−over frequency. Specifically, we hypothesized that simulator sickness was more probable when conflicting visual and inertial motion signals were presented at about 0.07 Hz than when the conflicting signals were at a higher frequency. The purpose of cross−over frequency range experiment was to examine this hypothesis.

3.2.2.1 Method

Subjects. 10 subjects were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance or balance disorders. Subject who were moderately susceptible to motion sickness were sought. Subjects were paid $15/ hour. The general protocol has been approved by the University of Washington Human Subjects Review Committee.

Apparatus. Visual scene motion was generated at 75 frames/sec using a Pentium III 750Hz processor and a 3Dlabs GVX1 graphics card. The visual image consisted of alternating vertical black and white stripes that subtended angles of 10°. The images were presented on the VR4 Research HMD. The images were oscillated around the subject's yaw axis at low frequency (0.03 and 0.05 Hz) or high frequency (0.20 and 0.25 Hz). Peak image angular velocities were about 50°/sec. A 90 foot−pound rate table (Contraves−Goertz) was used to oscillate subjects around their yaw body axis. Peak angular velocity: chair about 60°/sec. Center of balance dispersion was determined using the Chattecx balance system as described in 3.2.1.1.

Procedure. Following a brief description of the experiment, which included a review of symptoms listed in the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993), subjects completed a consent form and received payment. To generate conflicting motion signals, visual and inertial oscillation was presented at slightly different frequencies. Consequently, the phase relationship between the self−motion cues from the visual and inertial signals changed continuously (see Figure 3−6).

Figure 3−6 Phase Relationship between the Self−motion Cues from the Visual and Inertial Signals

Each subject received a maximum of 20 trials alternating between low and high frequency. Low frequency trials were A1 −− chair 0.08 Hz, scene 0.03 Hz and A2 −− chair 0.07 Hz, scene 0.05. High frequency trials were B1 −− chair 0.20 Hz, scene 0.25 Hz and B2 −− chair 0.18 Hz and scene 0.20 Hz. Beat frequencies were 0.05 Hz for A1 and B1 and 0.02 Hz for A2 and B2.

The order of trials was counter−balanced within sets of 4 trials, always starting with low frequency. For example A1, B1, A2, B2, B2, A2, B1, A1, A1 .... The initial trial was always a low frequency so that SS carry−over from one trial to the next worked against our hypothesis.

Center of balance dispersion and SSQ symptoms were recorded before the experiment started as well as during and after each trial. The experiment was terminated if stomach awareness persisted for longer than 1 m following a trial, if moderate nausea was reported, or at the subject's request.

3.2.2.2 Results

Useful data were obtained from 8 subjects. Figure. 3−7 illustrates data from a moderately susceptible subject who completed the full set of trials. Note that SS symptoms gradually increased across trials Note also that low frequency oscillation evoked more SS than high frequency oscillation.

Figure 3−7. Total SSQ Scores for low frequency chair / scene oscillation (dashed line) and high frequency out−of−phase oscillation (solid line) as a function of trial pair for one subject. The curves indicate that motion sickness accumulated across trials −− that there were carry−over effects. The curves gradually separate, which indicates that motion sickness was more severe following low frequency than high frequency trials.

SSQ values for “Nausea” and “Total Sickness” were calculated for each trial. Mean values for low frequency stimuli (A1 and A2) were greater than for high frequency stimuli (B1 and B2). Mean Total Sickness scores were significantly (t [1,7]= -2.33; $p = 0.012$) larger for low frequency chair / scene oscillation (195.5) than for high frequency oscillation (128.8). Mean

Nausea scores also were significantly ($t_{[1,7]} = -2.68$; $p = 0.014$) larger for low frequency oscillation (22.0) than for high frequency oscillation (13.4).

3.2.2.3 Discussion

The results from this experiment supported our hypothesis that simulator sickness may be most readily evoked by visual−inertial conflicts at the crossover frequency – the frequency where both the visual and the inertial self−motion systems are active. As predicted, subjects reported more motion sickness for low frequency conflicting motion stimuli than for higher frequency stimuli.

Reported differences in motion sickness evoked by low and high frequency conflicts were not large. It would be preferable to use a higher frequency conflict, 0.05 − 1.0 Hz, to compare with the low frequency one. We chose not to do so because high frequency motion overheats the rate table, which resulted in the expensive failure of the driver amplifier in a previous study.

3.2.3 Effects of FOV / Perceptual Style

The following experiment examined the effects of FOV on balance. Our hypothesis is that scene movement will evoke more postural disturbance with large FOVs.

3.2.3.1 Method

Subjects. 5 women and 5 men, ages 20 to 30, were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. All subjects reported that they had normal or corrected vision. Subjects were paid $10/ hour. The protocol was approved by the University of Washington Human Subjects Review Committee.

Apparatus. Visual scene motion was generated by computer software. This software accesses a series of digitized images to simulate scene motion. Two computer−generated scenes (city scene – Edmonds, WA and a simple scene − radial pattern) were used (see Figure 3−8). The images projected by a Box−Light projector (Box−Light, Inc.) were presented on a 3−foot dome, which has a nominal 180º x 180º FOV at a 640 x 480 pixel resolution. Subjects stood on a Chattecx balance platform (Chattecx Corp.)

Figure 3−8. Experiment Stimulus. The left shows the Edmond city scene. The right shows the simple radial pattern scene.

Procedure. Frontal visual scene roll oscillation was presented at a low frequency − 0.05 Hz (see Section 3.2.1 and 3.2.2). Peak scene angular velocity was constant at approximately 70º/sec. Scene update rate was approximately 40 frames/sec. Scenes were presented at 6 different of FOVs (+/−15º, +/−30º, +/−45º, +/−60º, +/−75º, +/−90º from the center of the visual field). Data were collected with the subjects in a sharpened Rhomberg stance. 4 trials (replicates) were collected in each stimulus condition. 10 sec periods of baseline data while viewing a static scene were collected before and after the moving scene trials. For the latter, the subjects looked at the moving scene for 10 sec while holding the support bars, assumed the Rhomberg position, and attempted to stand steady during the 10 sec data collection. The subjects also estimated the difficulty they experienced in maintaining their balance. Subjects' eyes were closed except during the visual stimulus trials. We determined all possible orders of experimental conditions and randomly choose a different order of FOV conditions for each subject. All subjects finished the simple scene condition first, then came back to finish the city scene condition one week later.

The following data were collected for each trial: stance break (yes, no); latency to stance break (10 sec maximum); subjective difficulty rating (1−10 scale); dispersion of center−of−balance. A stance break occurred when subjects uncrossed their arms or moved their feet off the force plates.

Figure 3−9. Mean and standard error. Standardized rating and dispersions as a function of field of view for simple and city scene. (Note: to preserve readability of the error bars, mean data points for the FOV conditions are staggered.)

3.2.3.2 Results

Results from this study are summarized in Figure 3−9. Subjects exhibited increased center−of−balance dispersion with increasing FOV for both the city and simple scenes. For the simple scene, there was a statistically significant main effect of FOV calculated using a repeated measures analysis of variance (ANOVA) [$F(5,5)=9.367$, $p < 0.05$]; for the city scene, the FOV main effect was also significant [$F(5,5)=7.72$, $p < 0.05$]. There was a significant main effect of FOV for the rating data in the city scene condition [$F(5,5)=9.801$, $p < 0.05$]. Post hoc analysis of the simple scene data indicated that, except for the 30°−60° interval, all the intervals were significantly different. The largest difference was for the 120°−150° interval. For the city scene data, the 60°−90°, 90°−120° and 150°−180° intervals were significantly different; the largest difference was for the 90°−120° interval.

3.2.3.3 Discussion

The experimental results supported our hypothesis. All the data showed the same trend – with increasing FOV, subjects exhibited more dispersion and reported more difficulty keeping their balance. For the city scene data, the dispersion increase for the 150°−180° interval was nearly as large as for the 90°−120° interval. Failure to observe ‘saturation’ at the extreme FOVs was surprising.

With increasing FOV, subjects received more information from their peripheral visual field, which apparently caused greater postural disturbance. These findings support the assertion that wide FOVs cause greater self−motion perception. Regarding the scene conditions, it seems that different scenes had different effects on postural stability. Subjects exhibited more dispersion and more balance difficulty with the city scene than with the simple scene. However, there were no statistically significant differences between the simple and city scene conditions for either the standardized dispersion or rating data. This is consistent with Keshner and Kenyon's (2000) report of no effect of scene complexity in their study of body segment responses when viewing a running architecture scene on a field of random dots.

For some subjects, postural disturbance appeared to saturate by the 150º FOV. Based on individual dispersion data at 150º, we separated subjects into two groups – group1 was a stable group (SG, dispersion below the median), group2 was the unstable group (USG, dispersion above the median). If we plot the data as exponential curves, as shown in Figure 3−10, it is clear that the city scene evoked greater postural disturbance than the simple scene. The shapes of the curves for both the SG and USG groups are similar. The curves differ primarily in their lateral position along the FOV axis. In our experiment, the most significant difference between FOV intervals occurred between 120°−150° for the simple scene. However, with the city scene the most significant difference occurred between 90°−120°. It is possible that if we presented different scene content, subjects would behave differently.

Figure 3−10. Dispersion as a function of FOV − best−fitting exponential curves for the SG and the USG in two scene conditions.

Each exponential curve can be fit to a regression model. For simple/USG, y=0.010x+0.785, R^2=0.825 (here y=ln[standardized dispersion], x=FOV); city/USG: y=0.009x+1.115, R^2=0.630; simple/SG: y=0.008x+0.920, R^2=0.716; for city/SG, y=0.008x+1.049, R^2=0.689. (See Table 3−1.) As can be seen, the coefficients for different scenes are similar but the intercepts are slightly different. For both slope and intercept regression coefficients, we examined mean differences between the city and the simple−radial scene conditions for the unstable group. Similar calculations were performed for the stable group. There were no statistically significant effects for either slope or intercept for simple/USG − city/USG (slope: t=−1.124, p=0.266; intercept: t=−1.797, p=0.078) and for simple/SG − city/SG (slope: t=0.43, p=0.669; intercept: t=−0.693, p=0.491). This suggests that both groups behaved similarly across scene conditions. There was also no statistically significant difference for city/USG − city/SG (slope: t=−0.275, p=0.784; intercept: t=0.766, p=0.447); but, for simple/USG − simple/SG there were significant differences for both slopes and intercepts (slope: t=−2.169, p=0.034; intercept: t=−2.166, p=0.037). This means that the SG and the USG behaved differently for the simple scene but not for the city scene.

Table 3−1. Regression model for groups and scene conditions. Y= ln (standardized dispersion), x= FOV

	USG	SG

Simple	Y=0.010x+0.785	Y=0.008x+0.920
City	Y=0.009x+1.115	Y=0.008x+0.689

It is interesting that the groups performed differently in the simple scene but not in the city scene. It is possible that the city scene provided more detailed horizontal and vertical cues than the simple scene. Apparently the city was more compelling; i.e., caused greater balance disturbance. This may explain why there was no difference between the USG and the SG for the city scene condition.

These results may also be related to so−called visual field dependent / visual field independent perceptual styles. Barrett, Thornton and Cabe (1968) examined the relationship between perceptual style and cue conflict. They found that field−dependent people experienced the most discomfort. Isableu, Ohlmann, Cremitux and Amblard. (1997) investigated the relationship between the perceptual style and postural control. They found that field−dependent people were less stable than field−independent people. The field−dependent people required dynamic visual cues to maintain their postural stability. In our experiment, the USG group exhibited larger balance disturbance than the SG group in the simple scene condition. The USG people may be more reliant on visual cues to maintain their balance. Individual differences in perceptual style may be important determinants of responses to scene content.

Why was the most significant FOV difference for the simple scene between 120° and 150° whereas the most significant difference for the city scene was between 90° and 120°? We suggest two possibilities. First, each eye has an individual FOV of 150° horizontally. The overlap region (binocular FOV) in the center averages 120° with 30°−35° monocular vision on each side. The combined horizontal FOV is 180°. The ideal display should have a total horizontal FOV of 180°, each eye having a 150° FOV, with binocular overlap of 120° FOV. Second, as suggested previously, the city scene provided more complex visual information and more meaningful objects. During post−experiment debriefing, subjects reported that they were more involved with the city scene. These considerations suggest the following question: would a *higher resolution* scene cause more disturbance than a *lower resolution* scene?

The results from this experiment indicated that postural stability varied as a function of display FOV when watching a moving scene. Subjects exhibited more balance disturbance with increasing FOV. Scene content may influence self−motion perception and postural stability. This implies that when we present scenes with different contents, different levels of interactivity, and different resolutions in immersive environments, different FOVs may be required to achieve a minimum level of ‘presence’. Future research will focus on interactions among resolution, FOV and scene content.

3.2.4 Effects of FOV / Resolution

Based on the FOV experiment described in Section 3.2.3, we concluded that further exploration of image resolution, FOV and scene content was appropriate. The purpose of this experiment is to examine relationships among these variables. Our hypothesis is that subjects will exhibit more postural disturbance with larger FOVs and higher scene resolution.

3.2.4.1 Method

*Subjects.*10 subjects (7 women and 3 men), ages 20 to 30, were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. All subjects reported that they had normal or corrected vision. Subjects were paid $10/hour. The protocol was approved by the University of Washington Human Subjects Review Committee.

Apparatus. Experiment setting the same as descried in Section 3.2.1.1.2. Visual scene motion was generated by computer software. Scene update rate was about 60 frames/sec. Two computer−generated scenes (fountain scene – University of Washington Fountain scene and simple scene − radial pattern) with two resolutions − 600 by 600 dpi and 256 by 256 dpi were used (see Figure 3−11). The back−projected images from a Kodak DL1100 projector (1024 x 768 pixel resolution − Kodak, Inc.) were presented on a 3−foot dome which has a nominal 180º x 180º FOV.

Figure 3−11: Experiment Stimulus. High resolution (600 x 600 dpi) fountain scene, and simple radial pattern scene (600 x 600 dpi).

Procedure Frontal visual scene roll oscillation was presented at a low frequency − 0.05 Hz (see Section 3.2.1.). Peak scene angular velocity was constant at approximately 70º / sec. Three different scenes (600dpi fountain scene, 600dpi simple scene and 256 dpi fountain scene) were presented at six different of FOVs (+/−15º, 30º, 45º, 60º, 75º, 90º from the center of the visual field). Data were collected with the subjects in a sharpened Rhomberg stance. 4 trials (replicates) were collected in each stimulus condition. 10 sec periods of baseline data while viewing a static scene were collected before and after the visual stimulus trials. For the experimental conditions, the subjects looked at the moving scene for 10 sec while holding the support bars, assumed the Rhomberg position, and attempted to stand steady during the 10 sec data collection. The subject's eyes were closed except during the visual stimulus trials. The order of FOV conditions was partially counterbalanced across all subjects. To avoid fatigue and learning effects, the experiment conditions were presented in two sessions with a 3 day interval between sessions. The following data were collected for each trial: stance break (yes, no); latency to stance break (10 sec maximum); subjective difficulty rating (difficulty in maintaining the Rhomberg stance, 1−10 scale); dispersion of center−of−balance. A stance break occurred when subjects uncrossed their arms or moved their feet off the force plates.

3.2.4.2 Results

Results from this experiment are summarized in Figure 3−12. Means for the dependent variables were calculated using repeated−measures ANOVA. For dispersion data, there was a statistically significant main effect of scene [$F(2,18)=61.978$, $p < 0.01$]; the main effect of FOV was also significant [$F(5,45)=50.621$, $p<0.01$] as was the interaction between scene and FOV [$F(10, 90)=5.949$, $P<0.01$]. Subjects responded differently to the different scenes; and, dispersion increased with increasing the FOV for all three scenes. Larger differences between scenes were obtained with the larger FOVs. For rating data, the main effects of scene, FOV and interaction were similar to those obtained using the dispersion data [($F(2,18)=35.597$, $P<0.01$; $F(5,45)=69.941$, $P<0.01$; $F(10,90)=2.058$, $P<0.05$, respectively). Selected *post hoc* analysis of the dispersion data indicated differences between FOVs; for all intervals (30°−60°, 60°−90°, 90°−120°, 120°−150°, and 150°−180°). The largest difference was for 150°−180°. For the rating data, there were differences for 30°−60°, 60°−90°, 90°−120°, and 120°−150° intervals. The largest difference was for 90°−120°.

Figure 3−12. Mean and standard error. Standardized rating and dispersions as a function of field of view for the simple and fountain scenes. (Note: to preserve readability of the error bars, mean data points for the FOV conditions are staggered.

To examine further the effect of resolution, we compared the high−resolution and low−resolution fountain scenes across the FOV conditions. For the dispersion data, the main effect of resolution was significant [$F(1,9)=60.010$, $p<0.01$] as was the interaction between resolution and FOV [$F(5,45)=6.116$, $P<0.01$]. Subjects exhibited increased dispersion with increased the FOV and resolution. With increasing FOV, the disturbance differences between resolutions increased. For rating data, the main effects of resolution and FOV were also significant [$F(1,9)=18.408$, $P<0.01$; $F(5,45])=65.530$, $P<0.01$, respectively]. However, the interaction between resolution and FOV was not significant for rating data.

To examine further the effect of scene content, we compared the high−resolution fountain and high−resolution simple radial pattern scene across FOV conditions. For dispersion data, the main effect of scene content was $F(1,9)=72.065$, $p<0.01$; the main effect of FOV was $F(5,45)=48.695$, $p < 0.01$; and the interaction between resolution and FOV was $F(5, 45)=10.000$, $P<0.01$. Subjects increased dispersion with increasing the FOV and more complex scene content. With increasing FOV, the disturbance differences between different scenes increased as well. For rating data, the main effects of scene, FOV were also different [$F(1,9)=56.911$, $P<0.01$; $F(5,45)=56.258$, $P<0.01$, respectively]. However, the interaction between scene content and FOV for the rating data was not significant.

3.2.4.3 Discussion

The experimental results supported our hypothesis. All the data showed the same trend – with increasing FOV, subjects exhibited more dispersion and reported more difficulty keeping their balance. For the standardized dispersion data, failure to observe "saturation" at the extreme FOVs was surprising. Subjects'standardized dispersion continued to increase up to the largest FOV across all three scene conditions. With increasing FOV, subjects received more information from their peripheral visual field and, this peripheral stimulation apparently caused greater postural disturbance. These findings support previous assertions that wide FOV cause greater self−motion perception and postural disturbance. They also suggest that people in a totally immersive environment might report more SS and presence.

In contrast to the dispersion results, there is a 'plateau' in the difficulty rating data. The plateau occurred between 120° and 150° FOVs across the three scenes. Possible explanations for this include the following. First, the subjects' perceptual scale for difficulty rating may have "saturated." During post−experiment debriefings, several subjects reported that they could not tell the difference between 150° and 180° FOV conditions, that it was hard for them to maintain balance in both conditions. Second, the rating data may reveal a "ceiling effect." Subjects frequently fell in both the 150° and 180° FOV conditions. The highest rating scale value − "10" – was automatically assigned when subjects broke stance or fell.

Scene content and resolution also appear to be important variables. Subjects exhibited greater postural disturbance and reported more difficulty in maintaining upright posture with the fountain scene than the simple scene when both were presented at high resolution. The fountain scene provides more 2−D depth cues and more meaningful or polarizing information than the simple scene. Also, there was a significant interaction between FOV and scene content. Subjects exhibited small differences with narrow FOVs but large differences with wide FOVs.

Subjects also exhibited greater postural disturbance and reported more difficulty in maintaining upright posture with the high−resolution fountain scene than the low−resolution fountain scene. Dispersion differences between high− and low− resolution scenes in the wide FOV condition were larger than in narrow FOV condition. Apparently, the higher spatial frequencies in the high resolution scene conveyed a greater sense realism than the low resolution fountain scene. This supports previous research that resolution is an important issue, as noted in the Introduction.

3.3 General Discussion

SS is frequently reported with exposure to systems designed to simulate motion of the observer (Kennedy and Stanney, 1996; Stanney and Salvendy, 1998). In the frequency response experiments 1 and 2, we determined the effects of frontal roll visual scene oscillation on balance. From the cross−over frequency range response experiment, we found that SS may be most readily evoked by visual−inertial conflicts in the frequency range where both the visual and the inertial self−motion systems are active. One procedure to minimize SS may be to limit simulated motion in this frequency range. (The underlying conceptual framework is similar to the one suggested by von Gierke and Parker (1994) to account for the frequency range over which linear oscillation evokes motion sickness. see Section 2.7)

Clearly, visual scene motion evokes self−motion in the lower range of the frequency response of the vestibular self−motion system (see Figure 3−5.). Attenuation of simulated motion in this range may alleviate SS. This is similar to DiZio and Lackner's suggestion (1997) that the visual scene be defocused when head motion exceeded a threshold velocity. Following Prothero's (1998) rest frame hypothesis, we may wish to present the IVB only when the simulated motion is in the low frequency / cross−over range. As noted in Section 2.6, several questions regarding the IVB need to be addressed. The second part of this dissertation will explore the properties of IVB.

As Experiments 3.2.3 and 3.2.4 indicate, small FOVs can evoke postural disturbance. Our results showed that even the 30° FOV evoked postural disturbance 1.2 times (Experiment 3.2.3) and 1.5 times (Experiment 3.2.4) (as large as the baseline condition for standardized dispersion and 1.8 times (Experiment 3.2.3) and 2 times (Experiment 3.2.4) more than baseline for standardized rating. Our data are consistent with Howard and Heckmann's (1989) results but not with those from the Brandt et al. (1973). Further experiments to reveal the differences in central and peripheral processing are required.

In summary, the results from experiments 3.2.3 and 3.2.4 indicated that postural stability varied as a function of display FOV, resolution and scene content. Subjects exhibited more balance disturbance with increasing FOVs, higher resolutions and more complex scene contents. This implies that when we present scenes with different contents, different levels of interactivity, and different resolutions in immersive environments, different FOVs may be required to achieve a minimum level of 'presence'. Future research will need to focus on relationships between independent variables including FOV, image resolution, scene content, and interactive control using presence and performance as dependent variables.

Chapter 4:

Part II: Intervention: the Independent Visual Background (IVB)

4.1 Introduction

The five experiments that described in this section explored characteristics of the IVBs. The first experiment examined the effects of IVBs on balance. We found that an IVB can reduce postural disturbance, which is consistent Prothero's findings (1998). The second experiment examined the effect of IVBs at different locations in the visual field. Surprisingly, the experimental results were different from our expectations. Subjects exhibited less center−of−balance dispersion and lower subjective difficulty ratings in the total FOV and central field IVB (grid) conditions than in no−grid and peripheral field conditions. In the third to the fifth sections, we investigate the effects of IVB spectral, temporal and stereographic perspective properties on balance.

4.2 Experiment

4.2.1 IVB Experiment

This experiment addressed the question: does an IVB reduce balance disturbance evoked by roll−axis visual scene motion? Our hypothesis is that IVB can reduce balance disturbance evoked by roll−axis visual scene motion.

4.2.1.1 Method

Subjects. 3 women and 5 men, ages 10 to 63, were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. All subjects reported they had normal or corrected vision. Subjects were paid $10/hr. The protocol was approved by the University of Washington Human Subjects Review Committee.

Apparatus. Visual scene motion was generated by WARP TV (Warp LTD). WARP TV uses a table look−up procedure to access a series of digitized video images to simulate scene motion. The scene used was a cartoon scene that has two cartoon characters in a room. The images were projected by a Boxlight projector and presented on a 3−foot diameter translucent dome which has a nominal 180° x 180° FOV and 640 x 480 pixel resolution. The equipment setting is the same as described in Section 3.2.1.1.2. A white grid (spatial frequency − 5 cycles per radian) was presented using a Kodak slide projector (Eastman Kodak Inc.) The IVB was superimposed over the entire cartoon scene at two brightness levels – dim (subjects just able to detect the IVB) and bright (subjects easily able to detect the IVB). The projected grid did not move relative to the dome. Subjects stood on a Chattecx balance platform (Chattecx Corp.) that automatically calculated dispersion around their center−of−balance based on signals generated by force plates under their feet.

Procedure. Frontal visual scene roll oscillation was presented at a low frequency − 0.05 Hz and a high frequency − 0.8 Hz. Peak scene velocity was constant at approximately 70° /sec. Subjects could see the rotating scene and the grid simultaneously. Data were collected with the subjects in a sharpened Rhomberg stance. One subject was unable to maintain the normal sharpened Rhomberg stance; for him the force plates were offset laterally 4 cm.

3 levels of IVB luminance (no, dim, and bright) were crossed with 2 levels of roll oscillation frequency (0.05 Hz and 0.8 Hz); these constituted the 6 visual stimulus conditions. 4 trials (replicates) were collected in each stimulus condition. 10 sec periods of baseline data, eyes closed in darkness, were collected before and after the visual stimulus trials. For the latter, the subjects looked at the moving scene for 10 sec while holding the support bars, assumed the Rhomberg position, and attempted to stand steady during the 10 sec data collection. The subject's eyes were closed except during the visual stimulus trials. The order of scene roll oscillation frequencies was randomized across subjects. The order of visual conditions was partially counterbalanced across subjects. The following data were collected for each trial: stance break (yes, no), latency to stance break (10 sec maximum), subjective difficulty rating (1−10 scale); dispersion of center−of−balance. A stance break occurred when subjects uncrossed their arms or moved their feet off the force plates

4.2.1.2 Results

Figure 4−1 summarizes the standardized scores across IVB luminance and roll oscillation frequency conditions. As shown in the standardized dispersion panel, subjects exhibited more disturbances in the no−IVB condition at the low frequency (0.05 Hz); however, there were no differences in disturbance as a function of IVB luminance during exposure to high frequency (0.8 Hz) scene motion. For standardized ratings (Figure 4−1, right panel), the results revealed the same trend; subjects reported more difficulty maintaining balance in the no−IVB condition during low frequency scene movement.

Figure 4−1. Mean and standard error. Standardized rating and dispersions as a function of IVB condition for high and low frequency scene roll oscillation. (Note: to preserve readability of the error bars, mean data points for the grid conditions are staggered.)

A repeated measures analysis of variance (ANOVA) of the dispersion data, indicated no statistically significant main effects of either the IVB or the frequency variables ($F[2,14]=3.38$; $F[1,7]=4.5$). However, there was a significant interaction between IVB and frequency ($F[2,14]=4.29$, $p<0.05$); for the rating data, there wasn't a statistically significant main effect of frequency ($F[1,7]=0.016$); However, there were statistically significant effects of IVB ($F[2,14]=8.018$, $p<0.01$) and the interaction between IVB and frequency ($F[2,14]=4.005$, $p<0.05$).

Figure 4−2. Standardized dispersions after combining the IVB data. For low frequency scene motion, subjects exhibited more dispersion when no IVB was present. There was no difference in dispersion for high frequency scene movement, as expected.

For further analysis, data from the dim and bright IVB conditions were combined and compared with the no IVB condition. The results are shown in Table 4−1 and Figure 4−2.

Table 4−1. Mean. Standardized scores for two different frequencies (0.05 Hz and 0.8 Hz) in the IVB and no−IVB conditions.

	0.05 Hz	0.8 Hz
Grid	0.74	0.63
No−Grid	1.26	0.63

Using repeated measures ANOVAs for the combined dispersion data, there were no statistically significant main effects of either the IVB or frequency variables ($F[1,7]=3.434$; $F[1,7]=5.072$). However, there was a significant interaction between IVB and frequency ($F[1,7]=6.743$, $p<0.05$). For the rating data, there wasn't a statistically significant main effect of the frequency variable ($F[1,7]=0.180$); however, there were statistically significant effects of IVB ($F[1,7]=11.766$, $p<0.05$) and the interaction between IVB and frequency ($F[1,7]=6.631$, $p<0.05$).

4.2.1.3. Discussion

Obviously, the IVB reduced balance disturbance for low frequency scene oscillation. This result supports our hypothesis and the suggestion that an IVB can be used in conditions where conflicting visual and inertial cues are likely to result in simulator or VE sickness.

Our data show that in the high frequency scene roll oscillation condition, there was little balance dispersion difference between the IVB and no−IVB conditions. However, in the low frequency condition, people reported more difficulty maintaining their balance and exhibited more dispersion. These results are reasonable. As noted previously, for high frequency scene motion (0.8 Hz), the low pass vection system is not activated; consequently, there is little or no balance disturbance. Little SS would be expected because there is no conflict between the visual and vestibular self−motion systems.

For low frequency (0.05 Hz) scene motion, the visual self−motion system is activated, which results in greater balance disturbance. SS would be expected because cues from the vestibular and visual systems are in conflict. However, when we provided an IVB, balance disturbance was dramatically reduced. We suggest the SS would also be reduced by this procedure (Kennedy and Stanney, 1996).

The suggestion that an IVB may reduce SS is consistent with anecdotal reports that users do not experience SS in augmented reality. In this case, the “real” part of the scene may provide an IVB.

Balance performance of subjects tended to be better in the bright IVB condition than in the dim condition during low frequency scene motion. This may reveal effects of attention or other cognitive factors. To address this issue, we asked whether the effects would differ if subjects focused on the scene or the IVB. In a preliminary study, we examined the balance performance of 3 subjects by presenting different instructions – “focus on the moving scene” or “focus on the IVB.” People did better keeping their balance when focusing on the IVB ($t=6.907$, $p<0.05$). However, it was very difficult to verify that subjects actually focused on the scene or IVB during the experiment. IVB brightness may have influenced the ability of subjects to follow the instructions; i.e. the bright IVB may be easier to attend to.

There is one potential problem with using an IVB to alleviate SS. Since the IVB is presented with the scene content of interest, it may be an “intrusive stimulus”. Users could reduced sense of sense of “presence” when an IVB is presented. To address this issue, we will be exploring procedures to make the IVB unnoticeable or even sub−threshold.

4.2.2 IVB Spatial Properties Experiment

This experiment was designed to address effects of IVB location in the visual field. Our hypothesis is that presenting the IVB in the peripheral visual field will be more effective for reducing postural disturbance.

4.2.2.1.1 Method – IVB Spatial Properties Experiment 1

Subjects. 12 volunteers (6 women, 6 men) in experiment 1. Subjects were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. All subjects reported that they had normal or corrected vision. Subjects were paid $10/ hour. The protocol was approved by the University of Washington Human Subjects Review Committee.

Apparatus. Visual scene motion was generated by WARP TV, which uses a table look−up procedure to access a series of digitized video images to simulate scene motion. The scene was a store in which two cartoon characters are placed. The images were back−projected on a 3 foot dome using a Boxlight projector. The nominal field of view (FOV) was 180° x 180° with 640 x 480 pixel resolution. Subjects stood on a Chattecx balance platform (Chattecx Corp.) that automatically calculated dispersion around the center−of−balance based on signals generated by force plates under their feet.

Procedure. Frontal visual scene roll oscillation was presented at 0.05 Hz. Peak scene velocity was constant at approximately 70°/sec. An earth−fixed grid (5 lines per radian in experiment 1, 9 lines per radian in experiment 2) superimposed over the moving scene was presented over the entire scene, in the central visual field (+/−32° from the center, and in the peripheral field (>47° from the center). For the peripheral visual field condition, the luminance of the peripheral grid was increased to be perceptually equal to that of the central grid. Data were collected with the subjects in a sharpened Rhomberg stance. 4 trials (replicates) were collected in each grid condition. 10−s periods of baseline data, eyes closed in darkness, were collected before and after the visual stimulus trials. For the latter, the subjects looked at the moving scene for 10 sec while holding the support bars, assumed the Rhomberg position, released the supporting bars and attempted to stand steady during the 10 sec data collection. The subject's eyes were closed except during the visual stimulus trials. The order of grid conditions was randomized (partially counterbalanced) across subjects. For each trial, center−of−balance dispersion was recorded and subjects rated their difficulty in maintaining balance (1−10 scale).

4.2.2.1.2 IVB Spatial Properties Experiment 2

Experiment 1 was replicated with the following changes. The visual scene was a simple black and white radial pattern, similar to a propeller. This image was back−projected by a Kodak DL1100 projector (1024 x 768 pixel resolution − Kodak, Inc.) onto the dome. The 8 subjects (4 women, 4 men) who participated in Experiment 2 stood on the balance platform leaning forward so that their heads are in the dome and the visual scene can cover all the subjects' visual field. The FOV was about 180° x 180°.

4.2.2.2 Results − IVB Spatial Properties Experiment 1 and 2

Subjects exhibited the less center of balance dispersion and lower subjective difficulty ratings in total FOV and central field grid conditions than in no−grid and peripheral field conditions Because of the large inter− and intra− subject variability, difficulty ratings and balance and dispersion scores were 'standardized': each visual trial score was divided by the average baseline performance for that subject. The standardized dispersion results from experiment 1 and experiment 2 are summarized in Figures 4−3. Differences in standardized dispersion as a function of grid condition were statistically significant [Experiment 1: $F(3, 33)=5.58$, $p<0.003$;Experiment 2: $F(3, 21)=12.284$, $p<0.003$]. For Experiment 1 dispersion data, post hoc analysis showed that there were significant differences between the no−grid and all FOV grid conditions, all FOV grid and peripheral field grid conditions, and central field grid and no−grid conditions. For experiment 2 dispersion data, post hoc analysis showed that there were significant differences between the no−grid and all FOV grid conditions, peripheral field grid and central field grid conditions and no−grid and central grid condition. For rating data, differences as a function of grid condition were also statistically significant [Experiment 1: F[3, 33]=19.297, p<.0.001Experiment 2: F(3, 21)=12.461, p<0.000]. For experiment 1, Post hoc analysis showed that all the conditions were significant different. For experiment 2, post hoc analysis indicated significant differences between no−grid and all FOV grid conditions, central grid and no grid and peripheral grid conditions, and no−grid conditions.

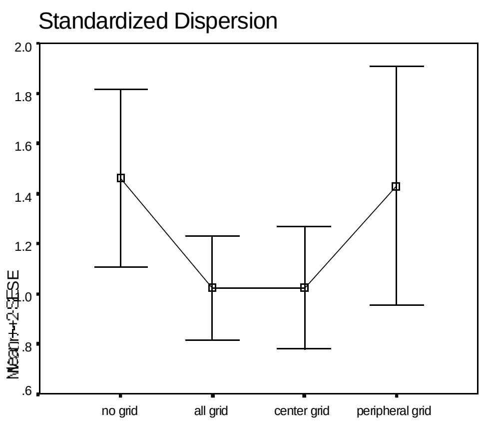


Figure 4−3. The left figure is dispersion data from experiment 1; the right figure is the dispersion data from experiment 2 (means and standard errors).

4.2.2.3 Discussion − IVB Spatial Properties Experiment 1 and 2

The hypothesis, which was derived from the two visual processing modes model (see Section 2.5), was not supported. For alleviation of scene motion−induced balance disturbance, an IVB located in the visual periphery was less effective than one located in the central visual field.

The failure of this experiment to confirm expectations suggests that the central visual field may by more sensitive to orientation and motion signals than is suggested by the two−modes model. Perhaps the central and peripheral fields exhibit different signal processing capabilities.

Several recent studies have challenged the Dichgans and Brandt’s (1978) “peripheral dominance hypothesis.” Based on studies of perceived heading accuracy, Warren and Kurtz (1992) suggested that periphery is less sensitive to radial optical flow than the central region. Stoffregen (1985) reported that postural adjustments were evoked by either radial or parallel (lamellar) optical flow in the central visual field but only by lamellar flow in the periphery. Further experiments will be required to determine whether the results from the present study reveal additional differences in central and peripheral processing.

Although our peripheral vision plays a special role in the perception of spatial orientation and motion, 'the rest frame' information may be processed by a different pathway. Our perceptual system might seek the rest frame from central visual field. Since our central vision is sensitive to object identification and discrimination, it may be easier to identify the IVB from cues presented to the central field. Possibly the central and peripheral regions differ in their ability to parse the moving scene and the static IVB. As above, further experiments are needed to examine these suggestions.

4.2.3 IVB Polarity Pilot Study

This purpose of this experiment was to examine how much IVB information is needed for reducing postural disturbance. Our hypothesis is that different types of IVBs can reduce postural instability evoked by scene motion.

4.2.3.1 Method

Subjects. 3 subjects were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. All subjects reported they had normal or corrected vision. Subjects were paid $10/hr. The protocol was approved by the University of Washington Human Subjects Review Committee.

Apparatus. Visual scene motion was generated by computer software. This software accesses a series of digitized images to simulate scene motion. A series of balloon scenes, which included different colors and numbers of balloons as presented. The images were projected by a Boxlight projector and presented on a 3−foot diameter translucent dome which has a nominal 180° x 180°

FOV and 640 x 480 pixel resolution. The equipment setting is the same as section 3.2.1.1.2.

Three types of IVB (vertical, horizontal and crossed grid) and three numbers of lines (1, 2, 3, 10, 35) were projected on the entire cartoon scene at two brightness levels – dim (subjects just able to detect the IVB) and bright (subjects easily able to detect the IVB). Subjects stood on a Chattecx balance platform (Chattecx Corp.) that automatically calculated dispersion around their center−of−balance based on signals generated by force plates under their feet.

Procedure. Frontal visual scene roll oscillation was presented at a low frequency − 0.05. Peak scene velocity was constant at approximately 70°/sec. Subjects could see the rotating scene and the grid simultaneously. The number of balloons changed at 5 sec intervals. In order to force subject's attention to the moving display, the subject's were instructed to count counting the balloons. Data were collected with the subjects in a sharpened Rhomberg stance.

2 levels of IVB luminance (dim, and bright) and 5 levels of lines (1, 2, 3, 10, 30) were crossed with 3 levels of IVB (vertical, horizontal and cross); these constituted the 30 visual stimulus conditions. 4 trials (replicates) were collected in each stimulus condition. 10 sec periods of baseline data, eyes closed in darkness, were collected before and after the visual stimulus trials. For the latter, the subjects looked at the moving scene for 10 sec while holding the support bars, assumed the Rhomberg position, and attempted to stand steady during the 10 sec data collection. The subject's eyes were closed except during the visual stimulus trials. The order of scene roll oscillation frequencies was randomized across subjects. The order of visual conditions was partially counterbalanced across subjects. The following data were collected for each trial: stance break (yes, no), latency to stance break (10 sec maximum), subjective difficulty rating (1−10 scale); dispersion of center−of−balance. A stance break occurred when subjects uncrossed their arms or moved their feet off the force plates

4.2.3.2 Results and Discussion

The experimental results are shown in Figure 4−4, 4−5. It supported our hypothesis – different types of IVBs could reduce SS. Note that for both the dispersion and rating data, luminance could be a critical factor. Most of the high luminance IVB condition subjects exhibited less postural disturbance then low luminance IVB conditions. For the horizontal and crossed lines, subjects' performance in 10 IVB condition was similar to the 35 lines conditions. For dispersion data, subjects' balance disturbance in high luminance conditions decreased as the number of IVB lines increased. Subjects' performance in horizontal and crossed line condition were similar. Vertical lines seemed not to help subject stabilize their posture. For rating data, in the high luminance IVB condition, subjects' difficulty ratings decreased with increased number of IVB lines. The same results were not found in the low luminance condition. Generally speaking, the experimental data support what we found from previous experiment. The crossed line IVB is apparently the best condition for helping people overcome postural disturbance. The vertical line IVB apparently did not help much. 10 lines of IVB gave the same results as 35 lines of IVB.

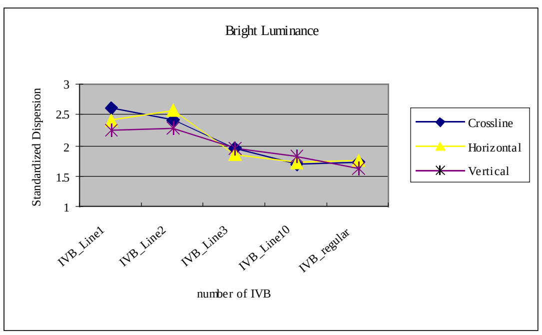


Figure 4−4 Standardized dispersion data for low luminance and high luminance IVB conditions.

Figure 4−5 Standardized rating data for low luminance and high luminance IVB conditions.

4.2.4 IVB Temporal Properties Pilot Study

The purpose of this experiment was to examine the effects of presenting the IVB intermittently rather than continuously. Our hypothesis is that there is no difference between intermittent and continuous IVBs for on reducing postural instability.

4.2.4.1 Method

Subjects. 3 subjects, were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. All subjects reported they had normal or corrected vision. Subjects were paid $10/hr. The protocol was approved by the University of Washington Human Subjects Review Committee.

Apparatus. Visual scene motion was generated by computer software. This software accesses a series of digitized images to simulate scene motion. The visual scene was a simple black and white radial pattern, similar to a propeller.). The back−projected images from a Kodak DL1100 projector (1024 x 768 pixel resolution − Kodak, Inc.) were presented on a 3−foot dome which has a nominal 180º x 180º FOV. The equipment setting was the same as section 3.2.1.1.2.

Three durations of IVB (18ms, 36ms, constant) were projected over the entire cartoon scene at three brightness levels – dim (subjects just able to detect the IVB), bright (subjects easily able to detect the IVB) and medium (luminance between dim and bright). Subjects stood on a Chattecx balance platform (Chattecx Corp.) that automatically calculated dispersion around their center−of−balance based on signals generated by force plates under their feet.

Procedure. Frontal visual scene roll oscillation was presented at a low frequency − 0.05. Peak scene velocity was constant at approximately 70°/sec. Subjects could see the rotating scene and the grid simultaneously. Data were collected with the subjects in a sharpened Rhomberg stance.

3 levels of IVB luminance (dim, medium and bright) were crossed with 3 durations of IVB (18ms, 38ms and constant); these constituted the 9 visual stimulus conditions. 4 trials (replicates)

were collected in each stimulus condition. 10 sec periods of baseline data, eyes closed in darkness, were collected before and after the visual stimulus trials. For the latter, the subjects looked at the moving scene for 10 sec while holding the support bars, assumed the Rhomberg position, and attempted to stand steady during the 10 sec data collection. The subject's eyes were closed except during the visual stimulus trials. The order of visual conditions was partially counterbalanced across subjects. The following data were collected for each trial: stance break (yes, no), latency to stance break (10 sec maximum), subjective difficulty rating (1−10 scale); dispersion of center−of−balance. A stance break occurred when subjects uncrossed their arms or moved their feet off the force plates

4.2.4.2 Results and Discussion

The results are shown in figure 4−6 and consistent with our hypothesis. Both dispersion data and difficulty rating data show the subjects' performance in the constant IVB condition was better than in the other condition. With increasing the durations of IVB, subjects' balance performance improved. Subjects' performance in all the IVB conditions was better than in the no−IVB condition. The results are consistent with our previous findings. Luminance was a dominant factor.

Figure 4−6. The left diagram is standardized dispersion data and right diagram summarized standardized rating data.

4.2.5 IVB Stereo and Foreground / Background Experiment

The purpose of this experiments was to examine the effects on balance of foreground / background manipulation of the IVB in a stereographic display. Our hypothesis is that IVB located “behind” the scene will reduce postural instability more than one in front of the scene.

4.2.5.1 Method

Subjects. 9 subjects (5 women and 4 men), ages 20 to 31, were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, or high susceptibility to motion sickness. All subjects reported that they had normal or corrected vision. Subjects were paid $10/hour. The protocol was approved by the University of Washington Human Subjects Review Committee and complied fully with the Helsinki declaration on the use of human subjects.

Apparatus. Visual scene motion was generated by computer graphics. Scene update rate was about 60 frames per sec. The visual scene was a simple black and white radial pattern, similar to a propeller. The back−projected images from a Kodak DP1100 projector (1024 x 768 pixel resolution – Eastman Kodak, Inc.) were presented on a 3−foot coated dome which had a nominal 180º x 180º FOV. To perceive the scene in stereo, subjects wore a shutter glasses − CrystalEyes (StereoGraphics Corp.) to perceive stereo that alternatively masked the left and right lenses and stood on a Chattecx balance platform (Chattecx Corp.) that automatically calculated dispersion around the center−of−balance based on signals generated by force plates under their feet. The equipment setting is the same as section 3.2.1.1.2.

Procedure Frontal visual scene roll oscillation was presented at a low frequency − 0.05 Hz (see Section 3.2.1.). Peak scene angular velocity was approximately 70º/sec. The nominal distance from the subject’s eye to the moving scene was 12”. The IVB (a grid) was presented over the entire scene at 3 positions (“in front” – 6.8”, barely in front, and behind – 23” from observer’s eye point) and at two brightness levels – dim (just detectable) and bright (easy to detect the grid). A no−IVB condition was used for comparison.

Data were collected with the subjects in a sharpened Rhomberg stance (Hamilton, Kantor, and Magee, 1989), subjects stood on the balance platform with one foot in front the other and with their arms crossed behind their backs, as described by Parker et al. (2001). The balance system collected data at a sampling rate of 100 Hz. 4 trials (replicates) were collected in each stimulus condition. 10 sec periods of baseline data while viewing a static scene were collected before and after the moving visual stimulus trials. For the experimental conditions, the subjects looked at the moving scene for 10 sec while holding the support bars, assumed the Rhomberg position, and attempted to stand steady during the 10 sec data collection. The subject's eyes were closed except during the visual stimulus trials. The order of IVB conditions was partially counterbalanced across subjects. The following data were collected for each trial: subjective difficulty rating (difficulty in maintaining the Rhomberg stance, 1−10 scale) and dispersion of center−of−balance

4.2.5.2 Results and Discussion

The results, which are shown in figure 4−7, do not support our hypothesis. As shown in the standardized dispersion panel, subjects exhibited more disturbances in the no−IVB condition than the three IVB location conditions. There were no differences in dispersion as a function of IVB luminance. For standardized ratings (Figure 4−7, right panel), the results revealed the same trend; subjects reported more difficulty maintaining balance in the no−IVB condition.

A repeated measures analysis of variance (ANOVA) of the dispersion data indicated a statistically significant main effect of IVB condition ($F [3, 24]= 12.111$, $p < 0.01$). Subjects exhibited less dispersion in all the IVB location conditions than in the no−IVB condition. However, there were no significant differences between IVB locations; also, there was no difference in response between luminance levels ($F [2,16] = 1.136$; $F [1,8] = 1.958$).

Figure 4−7. Mean and standard error. Standardized rating and dispersions for dim and bright luminance. (Note: to preserve readability of the error bars, mean data points for the FOV conditions are staggered.)

Similar results can found in the difficulty rating data. There was a statistically significant main effect of IVB condition ($F[3,24]=3.369$, $p<0.05$). Subjects reported that it was more difficult to maintain their posture in the no−IVB condition than in the IVB conditions. There were no significant differences due to IVB location; but there was a significant main effect of luminance ($F [1,8] = 8.639$, $p<0.05$)

The results showed that a stereo IVB reduced balance disturbance in a stereographic environment. This is consistent with previous findings (see Section 4.2.1, 4.2.2, 4.2.3, 4.2.4; Ohmi, Howard and Landolt, 1987; Brandt, Wist and Dichgans, 1975). Interestingly, compared to the Section 4.2.1, 4.2.2, 4.2.3, 4.2.4 data, subjects exhibited more dispersion and reported more difficulty maintaining their posture when exposed to 3D images than to 2D images. This suggests that stereographic displays may have a stronger effect on vection, which may imply a higher level of ‘presence’.

This experiment result failed to observe effects due to location in depth of the IVB. Brandt et al. (1973) examined stationary and moving stimuli presented simultaneously at different distances from the observer. Self−motion perception was determined primarily by the background stimulus. They reported that circular vection was more inhibited by stationary bars located behind the moving display than when the stationary bars were seen in front of the moving display. They concluded that self−motion perception relies on background information, whereas the object−motion perception depends on foreground information.

Ohmi, Howard and Landolt (1987) proposed that vection is under the control of whichever of two similar displays is perceived as background. Physical depth cues were not the crucial factor determining vection; rather, vection was determined by the display component that was perceived as more distant, even when it is nearer. They found that subjects experienced no vection whenever the more distant display was stationary.

In our experiment, even though the IVB was placed at different locations in depth stereoscopically it is always perceived to be in the background. This probably was a consequence of instructing the subjects to focus on the moving scene, not the IVB. If the IVBs were perceived as background regardless of stereoscopic location, our failure to observe differences due to stereoscopic depth location is consistent with Ohmi and Howard's results.

The role of luminance is also interesting. The curves suggest that differences between dim and bright conditions increased as the function of IVB location distance for both the dispersion and the difficulty rating data. A possible explanation for this is that when IVB was presented "in front", both the bright and dim IVBs, were perceived as "fuzzy" because the subjects focused on the moving pattern. When the IVB was presented "behind", subjects could detect the differences in luminance because the image was no longer fuzzy.

The experimental results are encouraging. One potential problem with using an IVB to alleviate SS is that the IVB is presented with the scene content of interest. Consequently it may be an "intrusive stimulus"; i.e., users could have a reduced sense of "presence" when an IVB is present. As noted in Section 4.2.1 we need to explore procedures to make the IVB unnoticeable or even sub−threshold.

The results of this experiment revealed no differences due to IVB stereographic location. These results suggest that the intrusiveness of the IVB could be reduced by presenting it in front of the scene at a low luminance level.

4.3 General Discussion

From this series of IVB experiments, it is clear that an IVB can reduce postural disturbance evoked by scene motion. We conclude that IVBs could be a solution for reducing SS. The results indicate several IVB properties that are important for reducing postural disturbance. Most of experimental results confirmed our hypotheses, but some did not. In Section 4.2.2, we expected that the peripheral IVB would reduce SS and the central IVB would not be as effective as either the whole field or peripheral IVB. The results were opposite to our hypotheses. It could be that the cognitive information processing for postural stability is different from that for SS or other higher−level cognitive activities. Luminance seems to be a dominant factor. More visible IVBs are more effective for reducing postural disturbance because they can provide more stable visual information in a moving scene. As described in Section 4.2.3, we know that we do not need many IVB grid lines to achieve improved performance. Based on the polarity experiment, we suggest that 10 grid lines produce the same effects as 35 grid lines. Different types of IVBs could be useful. In the experiment, the effects of horizontal lines were similar to those of crossed lines. It is possible to use different styles of IVB to make it more natural, to fit into visual stimuli of the VE. The IVB temporal properties experiment told us that increasing duration of the IVB improves postural stability. Although the experimental result was not statistically significant, it may be possible to explore the optimal the IVB exposure and duration time to make it more subliminal. The IVB also worked in the stereo condition. It is surprising that there were no statistically significant differences between locations of the IVB in space even though subjects’ preference is for presenting the IVB in the background of the visual scene. Our ultimate goal is to use IVBs to reduce SS / VE sickness in VEs. The experiments described above should help us to achieve this goal.

Chapter 5. Part III: Independent Visual background and Presence

5.1 Introduction

Following the discussion from Chapter 2 (literature review), Chapter 3 (dynamics of sensory conflict theory) and Chapter 4 (independent visual background), we examined the effects of FOV, scene content, resolution and properties of IVBs on balance disturbance. We determined a motion frequency where the summed response of the visual and inertial self−motion systems was maximized and labeled this the “cross−over” frequency. We tested the hypothesis that conflicting visual and inertial motion cues at this cross−over frequency would be more likely to elicit SS / VE sickness. We also explored the IVB properties including location in the FOV, polarity stereographic location in depth and temporal duration. The big question is: does the IVB really reduce SS? Two sections are included in this Chapter. The IVB / SS experiment described in Section 5.2.1 investigated the effectiveness of an IVB in reducing SS. Section 5.2.2 describes the relationship between SS and presence base on our empirical data.

5.2 Experiments

5.2.1 IVB/ SS Experiment

The purpose of this experiment was to investigate the effects of an IVB on SS. Our hypothesis is that the IVB can reduce SS during VE exposure.

5.2.1.1 Methods

Subjects. 7 women and 4 men, ages 18 to 32, were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. All subjects reported they had normal or corrected vision. Subjects were paid $15/hr. The protocol was approved by the University of Washington Human Subjects Review Committee.

Apparatus. We used a Real Drive driving simulator (Illusion Technologies International, Inc). It includes a real Saturn car (General Motors Company), three 230 cm x 175 cm screens on which images from 3 800 x 600 pixel SONY (SuperData MultiScan Projector VPH1252Q) projectors are displayed. A virtual world (Crayolaland) was generated by CAVE library software (developed by EVL, University of Illinois at Chicago) using a Silicon Graphics Onyx2 rack. Crayolaland is a cartoon world that contains a cabin, pond, flowerbeds and a forest. The IVB which was a 35 by 8 grid comprised of white lines, was presented behind the rear edge of Crayolaland. The FOV is 180º. Subjects wore a shutter glasses − CrystalEyes (StereoGraphicsCorp.) and sat in the car. See Figure 5−1. The Simulator Sickness Questionnaire (SSQ) (Kennedy et al, 1993) was used to evaluate the simulator sickness symptoms. E2i (developed in Human Interface Technology Laboratory by Lin and Duh, 2001, see appendix B) was used to evaluate user's enjoyment and presence.

Procedure. 2 levels of IVB conditions (no, yes) were crossed with 2 levels of stereo conditions

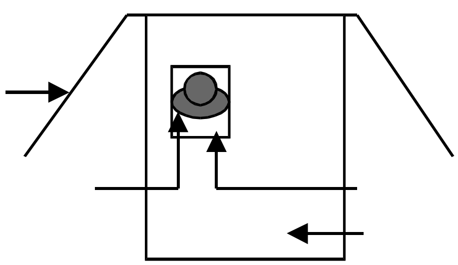


Figure 5−1 Experiment Setting

(no binocular disparity, binocular disparity); these constituted the 4 visual stimulus conditions. Since we are not intended to make subject serious motion sick, subject sat in the car and saw a 2 min pre−recorded "movie" of simulated movement of the car through Crayolaland. The simulation included acceleration, de−acceleration, left, and right turns and speed changes. The purpose of the pre−recorded "movie" was to produce a provocative stimulus so that subject would develop moderate SS symptoms. The subject's eyes were closed except during the visual stimulus trials. Each subject experienced all of the visual stimulus conditions. Subjects were randomly assigned (without replacement) to 1 of the 24 possible orders of the 4 visual stimulus

3 wall display

Subject

Balance platform

conditions. After each exposure, the subjects completed the SSQ and E2i questionnaire. Between trials, subjects rested until they reported that they were fully recovered from previous condition.

To reduce the placebo and expectation effects, subjects were not told the real experimental purpose. They were told that they were participating a virtual environment experiment which was addressing Presence issue. Below is part of the instructions:

> “Welcome to the driving simulator! You are participating in a virtual environment experiment. We are investigating whether the virtual environment gives you a sense of presence, how strongly the virtual environment evokes a sense of “being there”.
>
> This experiment includes 4 trials. After each trial, we will ask you several questions regarding your sense of presence. Since simulator sickness is a side−effect of exposure to virtual environments, we will also ask you to tell us about any simulator sickness symptoms”

5.2.1.2 Results and Discussion

The experimental results supported our hypothesis and are shown in Figure 5−2. As shown in the SSQ score panel, subjects reported more SS symptoms in the no−IVB condition than the IVB condition. For the E2i score panel, subjects reported higher E2i scores when the IVB was present than in the no−IVB condition.

Figure 5−2 Mean and standard error. SSQ score and E2i score for IVB condition. (Note: to preserve readability of the error bars, mean data points for the FOV conditions are staggered.)

A repeated measures analysis of variance (ANOVA) of the SSQ scores indicated a statistically significant main effect of IVB condition ($F [1, 10]= 8.546$, $p < 0.015$). Subjects exhibited less sickness in the IVB condition than in the no−IVB condition. However, there were no significant differences between stereo conditions; also, there was no effect due to the interaction between IVB and stereo conditions ($F [1,10] = 3.611$, $p=0.087$; $F [1,10] = 0.418$, $p=0.533$). For the E2i data, there were no statistically significant main effects of the IVB and stereo conditions or the interaction between IVB and stereo ($F[1,10]=2.151$, $p=0.173$; $F[1,10]=0.466$, $p=0.510$; $F[1,10]=0.002$, $p=0.968$).

The results showed that the IVB reduced simulator sickness in both stereo and non−stereo conditions. This result supports our hypothesis: the IVB can reduce simulator sickness. Also, it supports the suggestion that postural stability could be used as a criteria to assess SS.

One of the potential problems of presenting IVB, as was noted in Section 4.2.1.3, is that the IVB might disturb the sense of presence. The experimental results are encouraging. From the E2i data, presenting the IVB did not affect the user’s presence and enjoyment. On the other hand, the E2i scores are even higher when the IVB presented. Perhaps the IVB reduced subjects’ simulator sickness symptoms so that they felt more comfortable. During the post−experiment debriefing, subjects reported that they either do not notice when the IVB was presented or when they felt sick, they switched their attention to the IVB.

In this experiment, the IVB was presented at the edge of the virtual world. Its image was located in the periphery of subject's visual field. As noted in Section 4.2.2, we found that when presented in the peripheral visual field, the effect of IVB was the same as in the no−IVB condition. That result is not consistent with the findings from this experiment. One possible explanation is that the information processing associated with simulator sickness is different from that for postural instability. Although postural instability is thought to be a pre−cursor of simulator sickness, it could be processed by different channels from simulator sickness.

5.2.2 The Relationship between Simulator Sickness and Presence

Implementation of a useful IVB for regular use in simulators requires investigation of possible relationship between SS and presence. As noted in Section 2.9., there is no consistent relationship between SS and presence. In this section, we will explore the possible relationship between SS and presence based on the data collected in the driving simulator.

5.2.2.1. Method

Data from the 11 subjects collected in the experiment reported in Section 5.2.1 were combined with the data from 20 subjects from other experiments. (see Appendix C). These experiment used the same apparatus as the experiment in Section 5.2.1.

5.2.2.2 Results and Discussion

Table 5−1 presents the correlation coefficients relating SS, presence and enjoyment from the combined data. It summarizes there is a low non−significant negative correlation between E2i and SSQ scores. There is low non−significant positive correlation between presence and SSQ scores. However, there is a significant negative correlation between enjoyment and SSQ scores. The presence and enjoyment scores are significantly positively correlated with the E2i scores, as expected. This indicates that E2i questionnaire has high internal reliability.

The results are partly consistent with Nichols, Heldane and Wilson's (2000) findings. They used an HMD, Presence Questionnaire (PQ) developed by Singer and Witmar (1998) and the SSQ from Kennedy et al. (1993) were used to investigate the relationship between SS and presence. 20 subjects were tested by Nichols et al. They found a significant negative correlation between SS and presence. Nichols (1999) also reported a negative correlation between enjoyment and SS.

Table 5−1 Pearson correlation table of SSQ, E2i, presence and enjoyment score

	SSQ score	E2i score	Presence score	Enjoyment score
SSQ score	1	−.116	.156	−.399**
E2i score		1	.830**	.637**
Presence score			1	.126
Enjoyment score				1

**p<0.01

It is interesting that in our study the SSQ scores are positively correlated with the presence scores. This is different from some previous research (see Stanney and Salvendy , 1998) but consistent with Wilson, Nichols and Haldane's findings (1997). Welch (1997) also suggested that the greater the SS from a VE, the greater the increase in presence. Thus, what is the relationship between SS and presence? Stanney and Salvendy (1998) suggested that both SS and presence may correlated with intervening variables such as vection. Nichols, Haldane and Wilson (2000) agreed.

The combined data from 31 subjects who participated in 3 experiments were analyzed using a nonparametric smoothing density estimation method (see Bowman and Azalini, 1997; Simonoff, 1996). The results are shown in Figure 5−3, 5−4, 5−5, 5−6 and 5−7. As the figures indicate, there is no linear correlation between SSQ, presence and enjoyment scores. Regarding the relationship between enjoyment and SSQ scores, all of the figures show the same trend. For low SSQ values, SSQ and enjoyment appear to be positively correlated; however, with further increases in SSQ, enjoyment falls. Regarding the association between presence and SSQ scores in the wide FOV and stereo conditions, the trends are less clear and appear to differ for the narrow FOV versus wide FOV conditions as well as across stereo versus non−stereo. That is an interesting finding and suggests several points. First, it indicates the information processing may differ across FOV and stereo conditions. This would be consistent with two visual processing modes model, discussed in Section 2.5. Secondly, the association between presence and SS can not be described as a simple linear correlation. It may involve modulating variables such as FOV and stereo. We need to explore further those intervening variables to confirm possible associations.

Figure 5−3 Scatterplot with nonparametric smoothing density estimation of SSQ with presence and enjoyment scores. (31 subjects, 124 observation points)

Figure 5−4 Scatterplot with nonparametric smoothing density estimation of SSQ with presence and enjoyment scores in Stereo condition across all FOVS. (31 subjects, 82 observation points)

Figure 5−5 Scatterplot with nonparametric smoothing density estimation of SSQ with presence and enjoyment scores in non−Stereo condition across all FOVs. (31 subjects, 42 observation points)

Figure 5−6 Scatterplot with nonparametric smoothing density estimation of SSQ with presence and enjoyment scores in wide FOV condition (180° FOV). (31 subjects, 74 observation points)

Figure 5−7 Scatterplot with nonparametric smoothing density estimation of SSQ with presence and enjoyment scores in narrow FOV condition (60° FOV). (31 subjects, 30 observation points)

5.3 General Discussion

From the IVB/SS experiment, we concluded that the IVB can reduce SS. Interestingly, presenting the IVB did not reduce subjects' reported presence. One possible reason is that the IVB reduced distraction associated with SS symptoms and subjective discomfort. Also, because we presented the IVB in the peripheral visual field, it was not easily detected when subjects traveled through the virtual environment and therefore did not distract the subjects' attention from the simulation.

The experimental results also showed that the possible relationship between SS, presence and enjoyment. They demonstrated that the associations among SS, presence and enojyment are non−linear and might involve two or three modulating variables. Perhaps the most interesting finding is that a little bit of SS may be associated with enjoyment; but, as SS increases, the VE experience becomes less enjoyable. This finding could be interpreted following the cognitive appraisal approach pioneered by Schachter (e.g.1968). Subjects are fairly easy to recruit for "virtual reality" experiments, especially for those using a driving simulator because they anticipate a pleasurable experience. Initial SS symptoms such as increased sweating could be interpreted as "I'm having a good time; I'm excited." As SS symptoms increase to include, burping, stomach awareness and nausea, the "I'm having a good time" interpretation becomes less tenable; enjoyment decreases.

The further experiments are needed to examine possible modulating variables and the role of cognitive appraisal.

Chapter

6. Summary and Conclusions

Following the experiments and discussions presented above, we determined that the visual−vestibular cross−over peak frequency is around 0.07 Hz in the roll axis and that conflicting visual and inertial self−motion cues at this frequency were more likely to evoke SS than conflicting cues at a higher frequency. We developed a procedure, the IVB, to reduce postural disturbances and explored several characteristics of effective IVBs including spatial, temporal, stereo and foreground / background properties. We demonstrated that the IVB also alleviated SS. Finally, we examined relationships between SS, presence and enjoyment and found that the presence of an IVB apparently did not decrease presence. However, a little bit of SS may correlate with the subjects' enjoyment of a VE.

Several of our experiments used postural stability as a surrogate measure for accessing the effects of various IVBs. In these studies, we evaluated subjects' postural instability during the experiment rather than measuring postural instability after the experiment exposure. In subsequent experiments, we successfully used the IVB to reduce SS. Postural instability could be a precursor of SS. Thus, using postural instability measurement would be a good way to address SS because it is convenient and yields results relatively quickly. However, the results of the IVB spatial properties experiment (Section 4.2.2.) showed somewhat different results from the IVB / SS experiment (Section 5.2.1). Section 4.2.2 told us that the peripheral IVB did not help subjects to stabilize their postural instability. On the other hand, we used an IVB presented in the peripheral visual field to reduce SS. One possible reason to explain this apparent difference is that although the postural instability could be the precursor of SS, information processing of SS and postural stability might be through different channels, In the future, we should explore more about the underlying mechanisms of postural instability and SS. Investigating the association of postural instability with other physiological measures such as EEG, EKG, GSR etc. may be a good approach.

FOV is a critical issue in the development of VR systems. Other image quality issues such as resolution also play an important role. From our experiments, we know that increasing FOV may increase presence. The drawback of increasing FOV is that SS may increase too. According to our experimental results, subjects did not show saturation in their presence reports for the widest

FOVs we used. Also, as described in Section 3.2.3, the most significant FOV differences were between natural and simple scenes. We still need to know more about the FOV effects in different situations especially because the wide FOV display will become more popular.

For the future, it may be important to know the possible mechanism of information processing of vection with FOVs larger than 180º. This is an important topic for the VE industry. Differences between effects of vertical and horizontal FOV changes, which may be related to the distribution of our cone and rod receptor in the retina, could be a topic for future study. Determination of compromises between apparatus costs and customer requirements may be based on basic human factors studies such as these.

Our goal of developing SS mitigation is to maximize the sense of presence in VEs and minimize the side effects. The introduction of the IVB is the first step to reach this goal. As mentioned before, the potential problem with a grid IVB is that it may be an intrusive stimulus. It could reduce the user's sense of presence. Developing a robust, non−noticeable IVB will be an important topic for future investigation.

In this dissertation, Chapter 4 explored several characteristics of IVBs. A problem is that all the experiments used postural instability as the dependent measure. It would be appropriate to replicate those experiments using SS to confirm those findings. Also, investigating the user's performance, cognitive function and so on when the IVB is presented would also be an important topic for future studies.

Finally, we discussed relationships among enjoyment, presence and SS. We demonstrated that there are no simple linear correlations among those variables. The associations might be determined by several modulating variables such as stereo, FOV, or even individual differences between users. We noted that presence and SS are not simple issues because they involve not only by the attributes of the user, but also the characteristics of VE system. Future experiments will be needed to identify those variables and develop a model to help designers and engineers to develop better virtual interfaces.

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Appendix A Simulator Sickness Questionnaire

Instructions: Circle how much each symptom below is affecting you right now.

General discomfort	None	Slight	Moderate	Severe
Fatigue	None	Slight	Moderate	Severe
Headache	None	Slight	Moderate	Severe
Eye strain	None	Slight	Moderate	Severe
Difficulty focusing	None	Slight	Moderate	Severe
Salivation increased	None	Slight	Moderate	Severe
Sweating	None	Slight	Moderate	Severe
Nausea	None	Slight	Moderate	Severe
Difficulty concentrating	None	Slight	Moderate	Severe
"Fullness of the Head"	None	Slight	Moderate	Severe
Blurred vision	None	Slight	Moderate	Severe
Dizziness with eyes open	None	Slight	Moderate	Severe
Dizziness with eyes closed	None	Slight	Moderate	Severe
Vertigo (1)	None	Slight	Moderate	Severe
Stomach awareness (3)	None	Slight	Moderate	Severe
Burping	None	Slight	Moderate	Severe

(1) Vertigo is experienced as loss of orientation with respect to vertical upright.
(2) Visual illusion of movement or false sensations of movement, when not in the simulator, car, or aircraft.
(3) Stomach awareness is usually used to indicate a feeling of discomfort, which is just short of nausea.

Appendix B E2i Questionnaire

1. How much did looking at Crayolaland involve you, i.e. how much did the visual scene attract your attention?
2. To what extent did events such as noise occurring outside Crayolaland distract your attention from Crayolaland?
3. How compelling was your sense of objects moving through space?
4. How consist were experiences in the virtual environment, i.e. to what extent did you feel as though you were actually moving through Crayolaland?
5. How completely were you able to actively survey or search the environment using vision?
6. Were you involved in the memory task to the extent that you lost track of time?
7. How much did you have a sense of "being there" in the virtual environment?
8. During the time of the experience, which was strongest on the whole, your sense of being in the driving simulator room or in Crayolaland?
9. To what degree did you feel sad when the experience was over?
10. How much did you enjoy yourself during the experience?
11. How much would you like to repeat the experience you just had?
12. How interesting was your experience in Crayolaland?
13. How much would you be willing to pay to have the similar experience?
14. Please write down your comments about the experience with the system.

Over all:

A few personal questions.

1. What is your age? c under 16 c 16 to 25 c 26 to 35 c 36 to 45 c 46 to 55 c 56 to 65 c over 65

2. Are you female or male? c female c male

Thanks again for your help and interest!

Appendix C Experimental Procedures for E2i Data

20 subjects E2i data for Section 5.2.2. are from two separate experiments.

Experiment 1:

Subjects. 10 subjects were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. All subjects reported they had normal or corrected vision. Subjects were paid $15/hr. The protocol was approved by the University of Washington Human Subjects Review Committee.

Apparatus. The experiment settings are the same as Section 5.2.1.1

Procedure. Scenes were presented at 4 different of FOVs (+/−30º, +/−50º, +/−70º, +/−90º from the center of the visual field). Subject sat in the car and saw a 2 min pre−recorded "movie" of simulated movement of the car through Crayolaland. The simulation included acceleration, de−acceleration, left, and right turns, speed changes and rolling in the x−axis. The subject's eyes were closed except during the visual stimulus trials. Each subject experienced all of the visual stimulus conditions. Subjects were randomly assigned in the 4 visual stimulus conditions. After each exposure, the subjects completed the SSQ and E2i questionnaire. Between trials, subjects rested until they reported that they were fully recovered from previous condition.

Experiment 2:

Subjects. 10 subjects were recruited from the Human Interface Technology Laboratory subject pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. All subjects reported they had normal or corrected vision. Subjects were paid $15/hr. The protocol was approved by the University of Washington Human Subjects Review Committee.

Apparatus. The experiment settings are the same as Section 5.2.1.1

Procedure. 2 levels of FOV conditions (+/−30º, +/−90º from the center of the visual field) were crossed with 2 levels of stereo conditions (no binocular disparity, binocular disparity); these constituted the 4 visual stimulus conditions. Subject sat in the car and saw a 2 min pre−recorded "movie" of simulated movement of the car through Crayolaland. The simulation included acceleration, de−acceleration, left, and right turns, speed changes and rolling in the x−axis. The subject's eyes were closed except during the visual stimulus trials. Each subject experienced all of the visual stimulus conditions. Subjects were randomly assigned in the 4 visual stimulus conditions. After each exposure, the subjects completed the SSQ and E2i questionnaire. Between trials, subjects rested until they reported that they were fully recovered from previous condition.