"Conflicting" Motion Cues to the Visual and Vestibular Self-Motion Systems Around 0.06 Hz Evoke Simulator Sickness

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The basic question this research addressed was, how does simulator sickness vary with simulated motion frequency? Participants were 11 women and 19 men, 20 to 63 years of age. A visual self-motion frequency response curve was determined using a Chattecx posture platform with a VR4 head-mounted display (HMD) or a back-projected dome. That curve and one for vestibular self-motion specify a frequency range in which vestibular and visual motion stimuli could produce conflicting self-motion cues. Using a rotating chair and the HMD, a third experiment supported ($p < .01$) the hypothesis that conflicting cues at the frequency of maximum "crossover" between the curves (about 0.06 Hz) would be more likely to evoke simulator sickness than would conflicting cues at a higher frequency. Actual or potential applications of this work include a preliminary design guidance curve that indicates the frequency range of simulated motion that is likely to evoke simulator or virtual reality sickness; for simulators intended to operate in this frequency range, appropriate simulator sickness interventions should be considered during the design process.

INTRODUCTION

In order to act effectively, people require information regarding how they are oriented and whether they are stationary or moving with respect their environment. Self-motion information – information regarding how one is moving with respect to environmental reference frames – is critical for successful goal-directed behavior. Distortion of self-orientation and self-motion information may lead to postural disturbance and motion sickness.

Motion, Simulator, and Virtual Environment Sickness

This paper addresses the disturbance and sickness frequently reported as a result of exposure to systems designed to simulate motion of the observer (Kennedy, Lane, Berbaum, & Lilienthal, 1993; Kennedy & Stanney, 1996). If one follows a motion cue conflict approach (Griffin, 1990; Reason, 1978; Reason & Brand, 1975), one may attribute motion sickness to a mismatch between visual cues indicating that the observer is stationary and inertial cues indicating that the observer is moving (e.g., when a person views an apparently stationary visual scene in a cabin below the deck of a boat moving on a stormy sea).

As noted later, receptors that detect inertial motion include the vestibular apparatus. Numerous studies indicate that motion sickness requires an intact vestibular system (Griffin, 1990). Consequently, this paper focuses on visual and vestibular system responses.

The phenomenon of simulator sickness (SS) is similar to motion sickness (Stanney & Salvendy, 1998). Symptoms for both include nausea, disorientation, oculomotor disturbances, and ataxia (Kennedy et al., 1993). SS is thought to be caused, in part, by the same motion cue conflicts that result in motion sickness. Of course, there are many different types of simulators and virtual environments (VEs) that could evoke sickness in different ways (Kennedy, Berbaum,

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& Lilienthal, 1997). Most simulators and VEs have the common feature that the visual scene is artificial, as opposed to a real visual environment. In many simulators and VEs, the self-motion and self-orientation cues received by the vestibular receptors differ from those received by the visual receptors, and this cue conflict may be the basic cause for the sickness. (For an alternative to the motion cue conflict approach, see the Appendix: Postural Instability Theory.)

Self-Motion Detection

Self-motion is detected by several receptors, including the vestibular apparatus, which is located in the inner ear. Vestibular receptors detect head/body movement (i.e., inertial motion). People can readily distinguish up from down and detect peaks of displacement when they are oscillated from side to side, even when they are in darkness (Guedry, 1974). Responses to vestibular stimulation include postural adjustments and perception of self-motion (Howard 1986a, 1986b; Parker, 1980, 1991).

Motion of a visual scene can be interpreted as motion of an object, such as a flying bird, with respect to the observer. Alternatively, visual scene motion can be perceived as self-motion: The visual scene may be perceived as stationary, and the self may be perceived as moving with respect to that scene (Berthoz, 2000). Visually induced perceived self-motion, which is sometimes labeled *vection* (Howard, 1986a), may evoke postural disturbances, as can be observed in large-screen theaters such as IMAX. Illusory self-motion evoked by visual scene motion is the basis for many aircraft and driving simulators as well as VEs and amusement park attractions (Rolfe & Staples, 1986).

Scene motion conditions that facilitate the self-motion interpretation have been addressed in numerous studies. Full-field scene motion readily leads to perceived self-motion. When the visual scene is divided into stationary and moving components, the part of the scene that is perceived as "background" may determine perceived self-motion direction as well as postural disturbances (Dichgans & Brandt, 1978; Howard, 1986a).

Several neurophysiological studies indicate that self-motion signals from the vestibular apparatus are sent to the same brain stem nuclei that are stimulated by visually induced self-motion cues (e.g., Waespe & Henn, 1977). Apparently the neurons in these nuclei do not distinguish between inertial and visual self-motion cues under some conditions. However, the visual and vestibular self-motion systems differ in the latency of their responses to sudden stimulus onset. For moderately intense inertial stimuli (velocity changes), vestibular responses occur with a latency of less than 1 s (Guedry, 1974). In contrast, self-motion perception occurs with latencies on the order of seconds after scene motion onset (Wong & Frost, 1978).

The reports from Guedry (1974) and from Wong and Frost (1978) indicate that the frequency response of the vestibular self-motion system differs from that of the visual self-motion system. Examination of this frequency response difference and exploration of its implications for simulator and VE sickness are the major purposes of this paper.

Rationale

Likelihood of motion sickness as a function of motion temporal frequency has been examined in numerous studies (see Griffin, 1990). Conditions that evoke SS have also been examined previously (see Stanney & Salvendy, 1998). However, effects on SS associated with conflicting inertial and visual self-motion stimuli, taking into account motion frequency, have not been addressed previously by other laboratories.

Experiments 1 and 2 examined the visual self-motion system frequency response. Based on the frequency responses for the visual and vestibular self-motion systems, we hypothesized that conflicting motion cues at the frequency where the visual and vestibular curves cross each other would be most likely to evoke SS. This hypothesis was supported by Experiment 3.

Results from Experiments 1 through 3 led us to suggest a preliminary guidance curve for use in motion simulator and VE design. This preliminary curve is presented in the General Discussion section. Simulators or VEs designed to evoke self-motion perception in the guidance curve frequency range are likely to elicit SS. In this case, the designer should consider ways to ameliorate possible SS.

EXPERIMENTS 1 AND 2

The specific purpose of Experiments 1 and 2 was to determine the effects of visual scene oscillation around the participant's line of sight (scene roll oscillation) on postural balance.

Method: Experiment 1

Participants. Three women and 8 men, 23 to 63 years of age, were recruited from the Human Interface Technology Laboratory participant pool at the University of Washington. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. Participants were paid $15/hr. The gender distribution of volunteers approximately matched that of the participant pool. All participants completed an approved informed consent form. The participant pool and protocol for all the experiments presented in this paper were 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 WARP TV (Warp Ltd.). This application used a table look-up procedure to access a series of digitized video images to simulate scene motion. The scene was a tropical hillside that had evoked strong self-motion responses in previous studies (Prothero, Draper, Furness, Parker, & Wells, 1999). The images were presented on a VR4 (Virtual Research System Inc.) head-mounted display (HMD), which had a nominal 48° × 36° field of view (FOV) and 640 × 480 pixel resolution.

Participants stood on a Chattecx balance platform (Chattecx Corp.). The platform included a harness to prevent falling and support bars on the sides that were 36 cm apart and adjusted to elbow height. The participants stood on force plates (two each for left and right heels and toes) that were 12 cm wide and adjustable for different foot lengths. Signals from the force plates were digitized and analyzed to determine dispersion around the center of balance (COB). The sampling rate was 100 Hz. Dispersion was calculated by determining mean COB along the forward-rearward and side-to-side axes. The squared deviations of sampled points from the COBs were used to calculate a standard deviation: the dispersion index.

Procedure. Visual scene roll oscillation was presented at five frequencies: 0.8, 0.4, 0.2, 0.1, and 0.05 Hz. To avoid effects attributable to fatigue, potentiation, saturation, and so forth, the order of frequencies was randomized, without replacement, across participants. Peak scene velocity was constant across frequencies at approximately 70°/s.

Data were collected with the participants in a sharpened Rhomberg stance – that is, they stood unaided on the balance platform with one foot in front of the other and with their arms crossed behind their backs. This stance is often used in vestibular research (Hamilton, Kantor, & Magee, 1989).

Five successive trials (replicates) were collected in each visual stimulus condition. Baseline data, with the participant's eyes closed in darkness, were collected for 10 s before and after the visual stimulus trials. During visual stimulus trials, the participants looked at the moving scene for 10 s while holding the support bars. This was done to allow the long-latency visual self-motion response to develop. The participants then assumed the Rhomberg position and attempted to stand steady during the 10-s data collection. The participant's eyes were closed except during the visual stimulus trials. A minimum of 20 s elapsed between trials.

Subjective difficulty ratings and COB dispersions were collected for each trial. Difficulty ratings reflected participants' perceptions of their difficulty in maintaining a steady, upright posture. A rating of 1 indicated *very easy;* 10 indicated *very difficult.*

Method: Experiment 2

Experiment 1 was replicated with the following changes. The visual scene was back-projected by a Boxlight video projector onto a custom-made 0.92-m clear plastic dome. The side of the dome toward the projector was coated with matte-finish semiopaque spray enamel (ColorTouch™) to create a surface suitable for the back projection. The scene was a simple black-and-white radial pattern, similar to a black propeller on a white background. Four women and 5 men, 20 to 30 years of age, stood on the balance platform leaning forward so that their heads were in the dome. This was done to eliminate static visual cues from the dome support frame. The FOV was about 180° × 180°. The radial image was oscillated around the participant's line of sight, as in Experiment 1.

Results: Experiments 1 and 2

Because of large inter- and intraparticipant variability, difficulty ratings and balance dispersion scores were standardized: Each visual trial score was divided by the average baseline performance for that participant. This procedure allowed comparison across participants of the relative amplitude of balance disturbance evoked by different stimulus frequencies.

The results from Experiments 1 and 2, illustrated in Figure 1, show that balance disturbance was inversely related to scene oscillation frequency. The relative response amplitudes were normalized to permit comparison across experiments.

For both measures, the mean amplitudes for the baseline data (eyes closed) were essentially equivalent to those collected during exposure to the highest roll oscillation frequency (0.8 Hz). For Experiment 1, increasing postural disturbance was related to decreasing scene oscillation frequency for difficulty rating, $F(4, 40) = 3.29$, $p < .05$, and COB dispersion, $F(4, 40) = 5.34$. $p < .01$. Equivalent results were obtained from Experiment 2 for difficulty ratings, $F(4, 32) = 3.46$, $p < .05$, and COB dispersion, $F(4, 32) = 6.277$, $p < .01$.

Discussion: Experiments 1 and 2

Visual self-motion system frequency response. Subjective difficulty ratings and COB dispersion data from Experiments 1 and 2 are plotted separately in Figure 1. These four data sets are combined in a Human Interface Technology Laboratory (HITL) average curve. High-frequency (0.8-Hz) scene motion evoked little or no balance disturbance, which was surprising to most of the participants. Low-frequency motion (0.1–0.05 Hz) evoked much greater disturbance.

As noted in the Introduction, visually induced

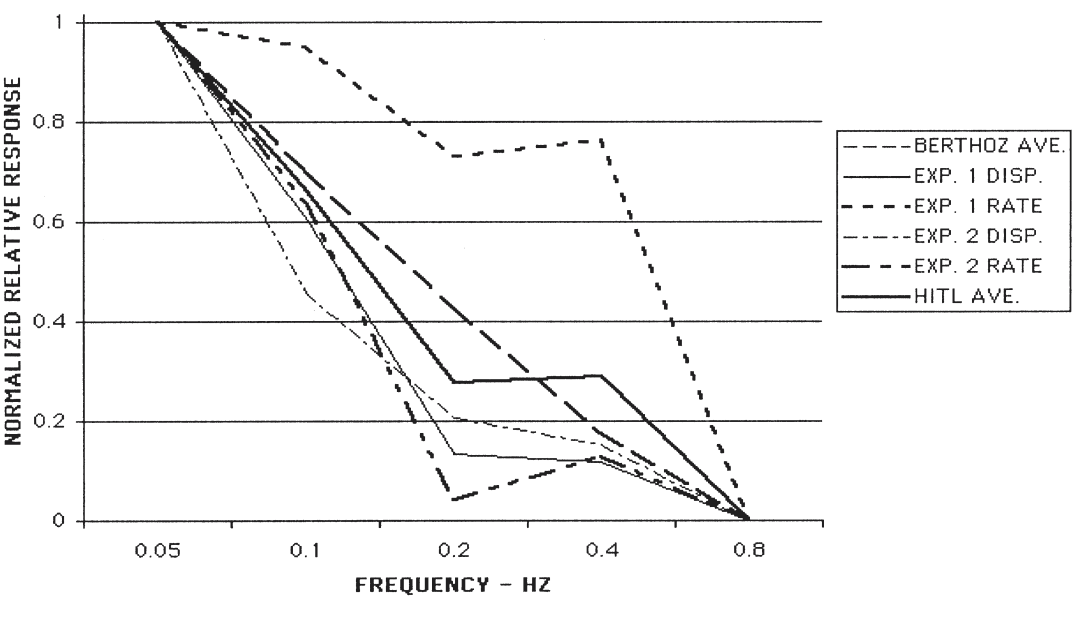

Figure 1. Postural instability (Disp.) and perceived difficulty maintaining upright posture (Rate) as a function of visual stimulus frequency. Exp. 1 Disp.: center of balance dispersion from Experiment 1; Exp. 1 Rate: subjective difficulty rating from Experiment 1; Exp. 2 Disp.: dispersion from Experiment 2; Exp. 2 Rate: difficulty rating from Experiment 2. HITL Ave.: combined average dispersion and rating data from Experiments 1 and 2. Berthoz Ave.: combined average self-motion perception frequency responses from three experiments cited by Berthoz et al. (1979).

balance disturbance and perceived self-motion are thought to derive from a common neurophysiological substrate. Balance disturbance data from our Experiments 1 and 2 are presented in Figure 1. This figure also presents results from three studies that examined perceived self-motion elicited by horizontal or vertical linear oscillation cited by Berthoz, Lacour, Soechting, and Vidal (1979). With the exception of the difficulty rating data from Experiment 1, the curves are remarkably similar. This supports the suggestion of a common frequency response for the neurophysiological substrate that mediates visually evoked self-motion and postural instability.

One might expect that different visual stimuli would produce different relationships between the amplitude of the effect and stimulus frequency. This would have resulted in a family of curves defining the visual self-motion system frequency response. The data presented in Figure 1 suggest that this expectation is wrong. First, for Experiments 1 and 2, there was a fourfold difference in FOV. Nevertheless, except for the Experiment 1 rating data, the shapes of the curves are quite similar. Second, the stimuli in Experiment 1 were head referenced and unaffected by body sway and the resulting head motion. This was an open-loop condition. The stimuli in Experiment 2 were referenced to the support surface and changed with body motion. This was a closed-loop condition. Despite these differences, the relationship between effect amplitude and stimulus frequency was quite similar in the two conditions.

In summary, these are interesting data because they indicate that the frequency response of the visual self-motion system is approximately the same across display types, FOVs, open-loop versus closed-loop postural compensation (HMD vs. dome), and angular (rotational) visual self-motion cues (Experiments 1 and 2) versus linear (translational) self-motion cues (Berthoz et al., 1979).

Vestibular self-motion system frequency response. Previous studies have reported vestibular response gain and phase with respect to inertial stimulus velocity. Reflex eye movements are one of the best indicators of vestibular function. In the frequency range of normal head movements – say, 0.1 to 5.0 Hz – the vestibular-ocular reflex gain (output with respect to input) is constant and the phase between eye velocity and head velocity is nearly zero. This suggests that the vestibular semicircular canals may be "designed" as transducers for head velocity (Milsum, 1966). Previous studies have also indicated that visual scene velocity is the appropriate metric for studying circular and linear perceived self-motion (Howard, 1986a). Consequently, when comparing visual and inertial stimulation, it is appropriate to use velocity as the reference. When studying the frequency response of the visual and vestibular systems, one could keep displacement, velocity, or acceleration constant while varying frequency. Based on previous research, velocity was held constant in our studies. Of course, displacement and acceleration covaried with frequency.

The semicircular canals, which can be modeled as integrating angular accelerometers, respond to rotational motion. Responses of the semicircular canals have been characterized in numerous studies (Howard, 1986b; Melvill Jones & Milsum, 1965). As with all biomechanical systems, output from the vestibular receptors varies with stimulus frequency. Because they behave as accelerometers, the vestibular receptors don't respond to constant-velocity ("DC") motion. Because they have mass components, there is an upper limit to the input frequencies that evoke responses from the vestibular receptors. Consequently, these receptors behave as band-pass frequency filters. As noted, the frequency range over which reflexes mediated by the semicircular canal receptors exhibit unity gain is 0.1 to 5.0 Hz. For the stimulus frequencies used in the present study, the semicircular canals may be described as high-pass frequency filters.

Visual-vestibular crossover. Widely cited data from Melvill Jones and Milsum (1965) are used to illustrate a high-pass vestibular frequency response in Figure 2. Data from the studies reported by Berthoz et al. (1979) are combined with the HITL average curve into a single visual self-motion frequency response curve in Figure 2. As for Figure 1, relative response amplitudes were normalized to permit comparison across self-motion systems. Clearly, the visual self-motion system exhibits low-pass frequency filter characteristics.

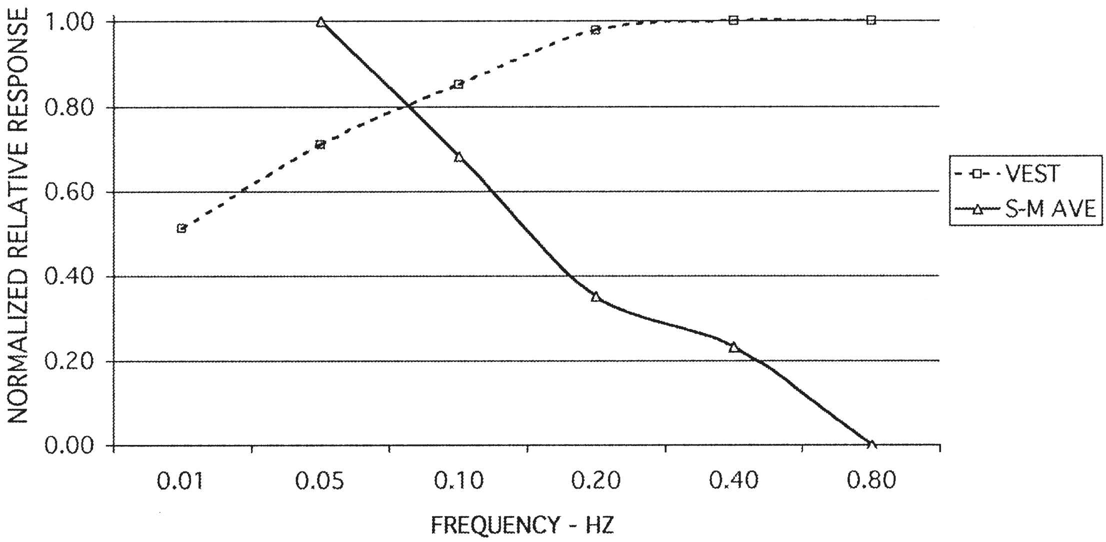

Figure 2. Visual-vestibular crossover. S-M Ave. (self-motion average): combined HITL Ave. and Berthoz Ave. (see Figure 1). Vest: vestibular frequency response. The crossover frequency, the frequency at which the summed gain from the visual and vestibular self-motion systems is maximum, appears be about 0.06 Hz.

The curves plotted in Figure 2 indicate the frequency range in which inertial self-motion cues detected by vestibular receptors could evoke SS as a consequence of conflict with visual self-motion cues. The visual self-motion frequency response crosses the vestibular self-motion frequency response at about 0.06 Hz. We call this the *crossover frequency* – the frequency at which the summed gain from these two self-motion systems is maximum.

We suggest that conflicting visual and vestibular self-motion cues at the crossover frequency would have the greatest potential to evoke SS. At the 0.06-Hz crossover frequency, the visual self-motion system has a relatively high gain – that is, visual scene motion evokes postural adjustments and perceived self-motion. At the same 0.06-Hz frequency, the gain of the vestibular self-motion system is relatively high; it also evokes self-motion responses. When conflicting motion cues are received by the visual and vestibular self-motion systems at frequencies where both produce strong effects, SS is likely. We hypothesized that SS would be more probable when conflicting visual and inertial motion cues were presented at about 0.06 Hz than when conflicting cues were at a higher frequency. The purpose of Experiment 3 was to examine this hypothesis.

EXPERIMENT 3

In this experiment, we examined the hypothesis that low-frequency conflicting visual/vestibular motion cues would evoke greater SS than would conflicting motion cues at a higher frequency. The frequencies of the visual and vestibular motion cues were approximately 0.06 Hz for the low-frequency stimuli and approximately 0.20 Hz for the high-frequency stimuli. Conflict was achieved by continuously changing the phase relation between the motion cues: Sometimes the visual and vestibular motion cues indicated the same direction of self-motion, and at other times they indicated opposite directions of self-motion.

Method: Experiment 3

Participants. Four women and 6 men were recruited from the HITL participant pool and were paid $15/hr. None reported a history of auditory disturbance or balance disorders. Participants who reported that they were moderately susceptible to motion sickness were sought.

Apparatus. Visual scene motion was generated at 75 frames/s using a Pentium III 750 MHz processor and a 3D Labs 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 HMD. Images were oscillated in azimuth around the participant's vertical axis (yaw axis) at low frequency or high frequency. Peak image angular velocities were about 50°/s.

A 90 foot-pound (122.04 newton meter) rate table (Contraves-Goertz) was used to oscillate seated participants around their vertical body axis at the frequencies described later. Peak angular velocity of the chair was about 60°/s.

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), participants completed a consent form and received payment.

To generate conflicting motion signals, visual and inertial oscillations were presented at slightly different frequencies. Conflict was produced because the phase relationship between the self-motion cues from the visual and inertial stimuli changed continuously (Figure 3). The procedure was based on the one used to generate auditory beats (Schiffman, 1990). Participants were asked not to move their head during trials.

Each participant received a maximum of 20 trials alternating between low and high frequency. Chair and scene motion frequencies and the resulting beat frequencies are presented in Table 1. (*Beat frequencies* are the frequencies at which the phase angle between scene and chair motion changed by 360°.)

The order of trials alternated between high and low frequency within sets of four as follows: A1, B1, A2, B2; B2, A2, B1, A1; A2.... The initial trial for each participant was always a low frequency so that SS carryover from one trial to the next worked against our hypothesis. (*Carryover* refers to the gradual accumulation of motion sickness symptoms during repeated exposures to a provocative motion environment, as discussed by Reason & Brand, 1975.)

SSQ symptoms were recorded before the experiment started as well as after each trial. The experiment was terminated if stomach awareness persisted for longer than 1 min following a trial, if moderate nausea was reported, or at the participant's request.

Results: Experiment 3

Exposure to varying-phase ("beating"), conflicting visual and vestibular motion cues elicited reports that perceived self-rotation velocity changed between quite slow and fast, even though the visual scene oscillation seemed to remain relatively constant. Most participants reported that they felt queasy after a few trials. Some reported that the paradoxical velocity changes caused that queasiness.

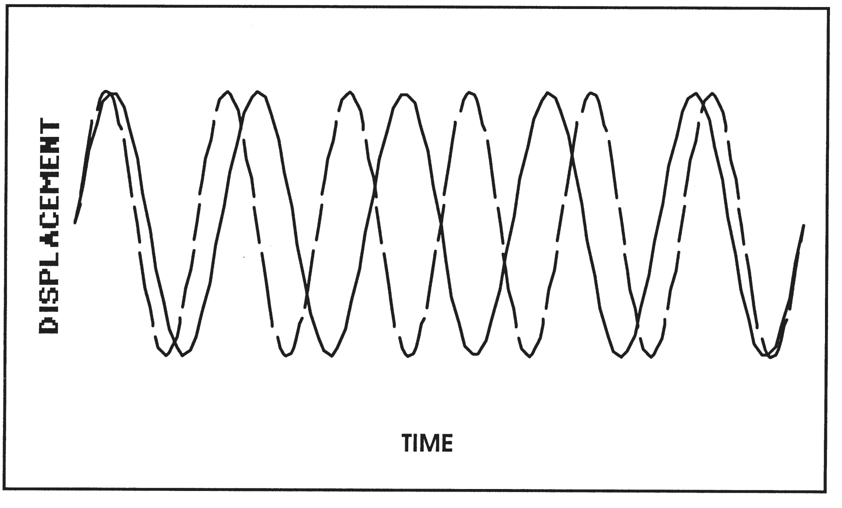

Figure 3. Visual-vestibular conflict was produced by oscillating the chair (solid curve) at one frequency and oscillating the visual scene (dashed curve) at a slightly different frequency. This resulted in a continuously changing phase relationship between the vestibular and visual stimuli, which was mildly provocative.

TABLE 1: Trial Frequency Properties

	Chair Freq.	Scene Freq.	Beat Freq.
Low-frequency trials			
A1	0.08 Hz	0.03 Hz	0.05 Hz
A2	0.07 Hz	0.05 Hz	0.02 Hz
High-frequency trials			
B1	0.20 Hz	0.25 Hz	0.05 Hz
B2	0.18 Hz	0.20 Hz	0.02 Hz

Useful data were obtained from 8 participants. 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 larger for low-frequency chair/scene oscillation (19.22) than for high-frequency oscillation (12.38), $t(7) = -0.416$, $p < .01$. Mean nausea scores also were significantly larger for low-frequency oscillation (22.13) than for high-frequency oscillation (13.75), $t(7) = -3.25$, $p < .05$.

Figure 4 illustrates data from a moderately susceptible participant who completed 18 trials. Note that SS symptoms gradually increased across trials. This illustrates the carryover effect. Note also that low-frequency oscillation evoked more SS than did high-frequency oscillation, as predicted.

Discussion: Experiment 3

The results from Experiment 3 supported our hypothesis that simulator sickness may be most readily evoked by visual-vestibular conflicts at the crossover frequency – the frequency at which the summed response from the visual and vestibular self-motion systems is maximum. Visual and vestibular self-motion cues were presented at a low frequency at which both systems provide strong signals to the central nervous system. By manipulating the phase relationship of those cues, a motion cue conflict was produced. As predicted, when exposed to conflicting motion stimuli, participants reported more SS at the crossover frequency (about 0.06 Hz) than at the higher frequency (about 0.20 Hz).

Reported differences in SS evoked by low- and high-frequency conflicts were not large. It

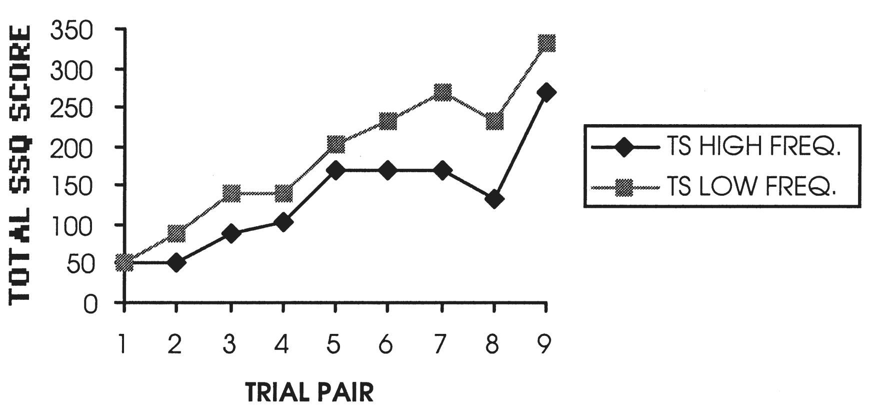

Figure 4. Total SSQ scores for low-frequency conflicting chair/visual scene oscillation (TS Low Freq.) and high-frequency conflicting chair/scene oscillation (TS High Freq.) as a function of trial pair for 1 participant. The total SSQ scores were larger for low-frequency conflict than for higher-frequency conflict. Motion sickness accumulated across repeated exposures to the conflict.

would have been preferable to use a higher-frequency conflict, 0.5 to 1.0 Hz, to compare with the low-frequency one. We did not do so because of equipment limitations.

To provide additional evidence for the "crossover model," one might be able to shift the crossover frequency by "fatiguing" either the visual or the vestibular self-motion system at a frequency close to the nominal crossover frequency. As a consequence, the crossover frequency should be shifted away from the fatiguing frequency, following a model similar to that underlying color afterimages.

GENERAL DISCUSSION

The research presented in this paper addressed SS under conditions of visual and vestibular self-motion system conflict that could be encountered in everyday situations. This effort may be viewed in the context of numerous suggestions for understanding and alleviating motion and SS.

Implications for Alleviating Simulator Sickness

Several procedures may be used to minimize sickness in motion simulators. One of these may be to limit simulated motion in the crossover frequency range. This is similar to DiZio and Lackner's (1997) suggestion that the visual scene be defocused or "grayed out" when head motion exceeds a threshold velocity. Another possible intervention might be an independent visual background (IVB). Prothero et al. (1999) reported that participants exhibited fewer disturbances from scene motion presented on an HMD when they could see stationary laboratory walls (the IVB in this experiment) behind the moving scene than when the static walls could not be seen. Duh (2001) demonstrated that faint static grid lines (the IVB in his experiment) superimposed over a moving scene reduced postural disturbance evoked by scene motion. Recently, Lin, Abi-Rached, Kim, Furness, and Parker (2002) extended the work by Duh and determined that an IVB also alleviates SS. It may be useful to present the IVB only when potentially conflicting simulated motion cues are in the frequency range at which the visual and vestibular self-motion systems are active.

Motion Sickness Frequency Response

Relationships between motion sickness and motion stimulus variables, including frequency, magnitude, direction, and duration, have been addressed in numerous studies. Because it is thought to be a prime cause of motion sickness in some ships, vertical oscillation, sometimes called "heave," has been extensively studied. For example, Lawther and Griffin (1987) found the highest incidence of vomiting during vertical oscillation at 0.03 to 0.50 Hz. The British Standards Institution (1987) standard 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. Golding, Mueller, and Gresty (2001) reported that motion sickness symptoms were maximum during horizontal side-to-side oscillation at about 0.2 Hz. Recent studies have attempted to refine existing knowledge of motion sickness by addressing factors that modulate the motion sickness response, including visual stimulus factors, body orientation (seated vs. supine, etc.), and direction of inertial motion with respect the participant (Lo & So, 2001; Mills & Griffin, 2000).

Although horizontal (side-to-side) and vertical (up-down) inertial oscillation has been examined by several investigators, we are unaware of studies that have addressed the motion sickness frequency response as a function of oscillation around the vertical body axis (yaw oscillation) in an upright observer. Further, we are unaware of previous studies in which conflicting visual and vestibular self-motion cues were manipulated in the frequency domain, as in our Experiment 3.

Implications of Simulator/VE Design Guidance Curve

Curves relating likelihood of sickness to stimulus frequency, such as the British Standards Institution (1987) standard for vertical inertial motion, are intended to assist vehicle designers. A similar guidance curve that could assist designers of motion simulators and VEs is suggested by this study.

Figure 2 illustrates the frequency responses for the visual and vestibular self-motion systems and shows the frequency of maximum summed activity for the two systems. The area under the two curves may summarize the frequencies of potential motion cue conflict between the two systems. In other words, the area under the curves defines the frequency range in which both the visual and the vestibular self-motion systems are responsive.

The area under the curves in Figure 2 is redrawn and presented in Figure 5. This resulting curve, labeled "Vis-Vest Simulator Sickness," indicates the frequency range in which conflicting visual and inertial motion cues would be likely to evoke simulator/VE sickness. The highest probability of simulator/VE sickness would be at the crossover frequency. Less sickness would be expected at frequencies above the crossover because visual self-motion system responsiveness is reduced in this frequency region; similarly, less sickness would be expected at frequencies below the crossover because the vestibular self-motion system response is reduced in this frequency region.

We propose the curve labeled "Vis-Vest Simulator Sickness" as a preliminary design guidance curve. Based on simulator components and properties, such as a moving versus a stationary base, designers should be able to estimate whether the simulator is likely to produce conflicting visual and vestibular self-motion cues. Depending on the intended use, it should also be possible to estimate the frequency range of possible conflicting motion cues. If conflicting motion cues in the frequency range defined by the "Vis-Vest Simulator Sickness" curve are likely, designers and users may need to consider procedures to alleviate potential simulator/VE sickness, such as those discussed in the section titled Implications for Alleviating Simulator Sickness.

Of course, further research is needed to support the suggested preliminary design guidance curve proposed in this paper.

CONCLUSIONS

In summary, the first two studies reported here examined the frequency response of the

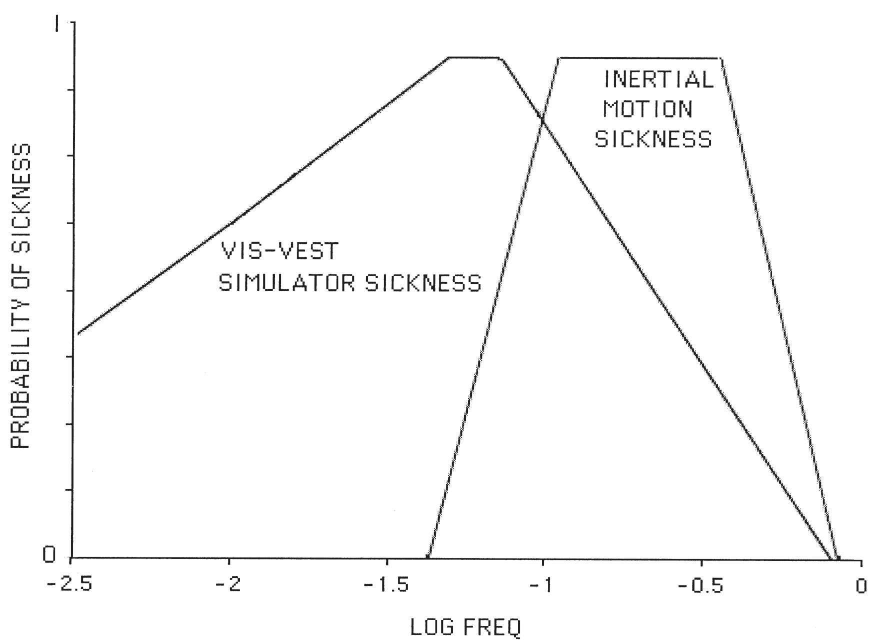

Figure 5. The curve labeled "Vis-Vest Simulator Sickness" suggests a possible relationship between frequency of conflicting visual and inertial motion cues and likelihood of sickness that could be used to guide design of simulators and virtual environments. The curve labeled "Inertial Motion Sickness" is the British standard relating vertical motion frequency to the relative likelihood of sickness that has been previously used for design guidance.

visual self-motion system. The data from those studies as well as data from other laboratories indicate that the visual self-motion system does not respond to high-frequency scene motion (>1.0 Hz) but is responsive to very low frequency motion (<0.1 Hz). In other words, the visual self-motion system exhibits low-pass frequency filter characteristics. Other investigators have characterized the vestibular self-motion system frequency response. In the frequency range of this study, the vestibular self-motion system exhibits high-pass frequency filter characteristics. In combining the curves, we suggested a motion frequency at which the summed response of the visual and vestibular self-motion systems was maximum, which we called the *crossover frequency.* The third study examined the hypothesis that conflicting visual and inertial motion cues near this crossover frequency, about 0.06 Hz, would be more likely to elicit SS than would conflicting cues at a higher frequency, about 0.20 Hz. These studies are part of a broad, continuing effort to characterize and alleviate SS. The results also have implications for design of motion simulators and VEs.

APPENDIX: POSTURAL INSTABILITY THEORY

Cue conflict is not the only approach to simulator/VE sickness. As an alternative to the traditional sensory conflict approach, Riccio and Stoffregen (1991) proposed a "postural instability theory" to explain the SS phenomenon. 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. A VE is a novel environment, different from the normal world. Riccio and Stoffregen suggested that people need to learn new "patterns" to control their postural stability in a VE. Until this learning is completed, they may experience SS. Postural disequilibrium should precede the motion sickness symptoms. Several studies support this hypothesis (Stoffregen, Hettinger, Haas, & Smart, 2000; Stoffregen & Smart, 1998). The postural instability theory may also explain the results from Experiment 3. Replication of Experiment 3 using a postural stability dependent variable, in addition to the SSQ, would permit examination of this possibility.

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