Effects of Simulated Motion Frequency in Virtual Environments

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ABSTRACT

Two studies used virtual environments (VEs) to examine the role of simulated motion frequency in visually-induced motion and simulator sickness (SS). Predictions were derived from the "crossover" hypothesis, which suggests that restricting simulated motion frequency in the region where conflicting motion cues to the visual and vestibular self-motion systems are readily detected (around 0.07 Hz) should reduce SS. Results from both studies were consistent with predictions.

Keywords

Visual motion frequency, simulator sickness, self-motion perception

INTRODUCTION

Self-motion perception and associated orientation reflexes derive from cues detected by inertial / physical motion receptors, primarily those located in the inner ear vestibular apparatus, and from the visual self-motion system. Visually-induced self-motion is familiar to anyone who has slammed her brakes while sitting in a stationary car when the neighboring car slowly creeps forward. Normally, the visual and inertial systems work together to permit accurate self-motion perception.

Motion and simulator sickness have been approached using numerous models. Among these is the cue conflict model [5], which suggests that motion / simulator sickness is evoked when self-motion cues from inertial and visual receptors indicate different directions and rates of motion. Inertial self-motion cues are detected by vestibular receptors that can be modeled as integrating linear accelerometers; consequently, these receptors are unable to detect constant velocity inertial motion. As has been demonstrated in numerous studies, it is reasonable to expect that motion sickness severity associated with conflicting cues would vary with either real or simulated motion frequency.

Previous research [14, 4] addressed the question, how does SS vary with simulated motion frequency? A visual self-motion frequency response curve was determined using a Chattecx posture platform that provided quantitative assessment of postural stability. Visual disturbance of posture was produced by frontal rotation (around the participant's nasal-occipital axis) of a black and white propeller-like visual stimulus. The resulting visual self-motion frequency response curve has the form of a low-pass filter. That curve and one for vestibular self-motion system, which exhibits high-pass frequency filter characteristics, specify a frequency range, which was labeled the "crossover range," where vestibular and visual motion stimuli could produce conflicting self-motion cues. At approximately 0.07 Hz the summed gain from the visual and vestibular self-motion systems is maximum, as shown in Figure 1.

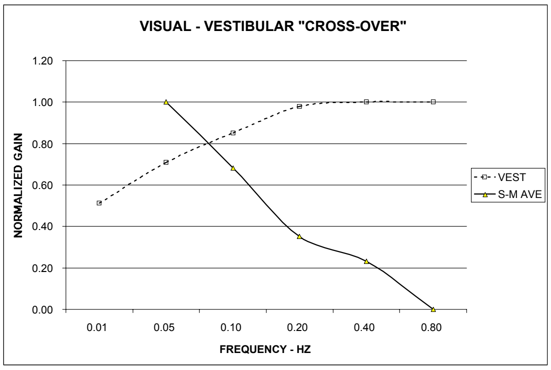

Figure 1. Visual-Vestibular Crossover [4]. S-M AVE -- average visual self-motion frequency response; VEST: vestibular self-motion frequency response.

Duh *et al*. [4] examined the hypothesis that conflicting visual and inertial self-motion cues in the 0.07 Hz frequency range would evoke greater SS than conflicting cues at a higher frequency. Participants were oscillated around their longitudinal (yaw) axis while seated upright on a rotating chair. Conflicting visual self-motion cues (oscillating vertical black and white stripes) were presented on a head-mounted display. The oscillation frequencies of chair rotation and visual scene rotation differed slightly so that there was a continuous change in the phase angle between them, which was analogous to acoustical "beats". In other words, sometimes the visual and inertial self-motion cues indicated motion in the same direction, and at other times, the self-motion cues indicated motion in opposite directions. The results indicated that conflicting self-motion cues in the 0.07 Hz frequency range produced greater SS than conflicting self-motion cues at a higher frequency.

EXPERIMENT 1. EFFECTS OF FIELD OF VIEW AND VISUAL MOTION FREQUENCY ON SS

This experiment addressed the possibility that the visual-vestibular crossover frequency could be altered as a function of varying field-of-view (FOV). As illustrated in Figure 2, the relative gain (ordinate) of the visual self-motion system curve (Visual) would be larger when the FOV is large and vice versa. Consequently, the crossover frequency should be higher in the larger FOV condition than with a smaller FOV.

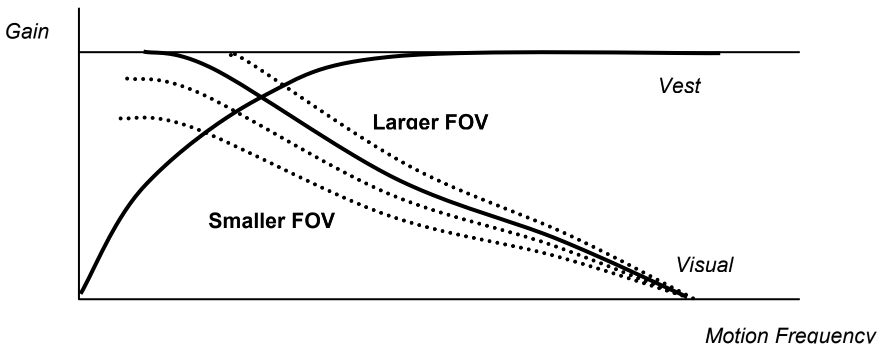

Figure 2. The proposed model of shift of the visual self-motion system frequency response curve with different FOVs. See text.

The specific hypothesis was that SS evoked using the scene motion in a mid-range frequency (around .07 Hz) would be greater than that with higher or lower level motion frequencies. Expected results are illustrated in Figure 3.

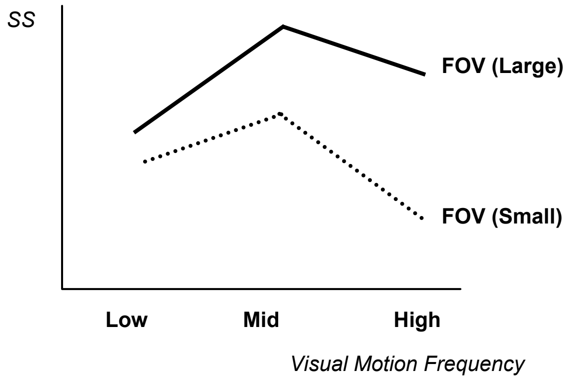

Figure 3. Hypothesized effects of visual motion frequency and FOV on SS.

Method

Participants

20 participants, 11 women and 9 men, ages 18 to 35, were recruited from the Human Interface Technology Laboratory participant pool. None reported a history of auditory disturbance, balance disorders, back problems, or high susceptibility to motion sickness. All participants reported that they had normal or corrected-to-normal vision. Participants were paid $15. The University of Washington Human Participants Review Committee approved the protocol.

Apparatus

A Real Drive driving simulator (Illusion Technologies International, Inc.), including a full-size Saturn car (General Motors Company), 3 800 x 600 pixel Sony Superdata Multiscan VPH-1252Q projectors, and 3 230 x 175 cm screens, was used. A virtual world (Crayoland) was generated by the CAVE® software library (developed at the EVL, University of Illinois, Chicago) using a Silicon Graphics Onyx2 system. Crayoland is a cartoon world that includes a cabin, pond, flowerbeds, and a forest. Additional software permitted the experimenters to steer using a handheld controller SpaceOrb Joystick (Spacetec IMC Co.) and then replay the prerecorded trajectories through Crayoland. Continuous roll axis oscillation could be added to the motion trajectory. The computer-generated images were presented on the 3 screens as a panoramic scene and subtended a 220º horizontal FOV. The scene was presented in stereo using CrystalEyes™ stereo glasses (StereoGraphics Inc.) that alternately masked the left and right lenses. Participants sat in the driver's side of the car on a wood plate that replaced the driver’s seat.

Procedure

Participants were “driven” through the Crayoland VE along a trajectory with forward translation set at a slow constant velocity. Identical pre-recorded 90-sec trajectories around the VE were presented using 6 different viewing conditions. The visual scene was presented with a wide FOV (+/-90º from the center of the visual field) combined with continuous roll scene oscillation (+/- 60º) at low (0.035 Hz), mid (0.080 Hz), or high (0.213 Hz) frequency level for 3 conditions. For the other 3 conditions, the scene was presented with a narrow FOV (+/-30º) and was oscillated at the same 3 frequencies. The Revised Simulator Sickness Questionnaire—RSSQ [8,9] was used to assess disturbance associated with these VE exposure conditions.

There were 6 90-sec experimental trials. Following each trial, participants repeated the RSSQ. Participants rested at least 5-min between trials. The rest intervals were prolonged as needed to maintain a low pre-trial SS level. Participants were randomly assigned, without replacement, to 1 of the 720 orders of the 6 experimental conditions. Each experiment took about 1.5 hours.

Results

Two-way repeated measures ANOVAs were calculated to examine the effects of visual motion frequency and FOV on RSSQ. Based on the normal quantile-quantile plots, the residual plots, and Levene's test of equality of error variances, a logarithmic transformation of the RSSQ scores was performed to satisfy the assumptions of the analyses. As predicted, participants reported higher scores with a wide FOV [$F\ (1,19) = 8.191$, $p = .010$], and the mean scores at mid frequency level were higher than the low and high frequency levels. However, the scores were not statistically different across different motion frequency conditions [$F\ (2,38) = 1.320$, $p = .276$]., The interaction between FOV and visual motion frequency was not significant for the transformed RSSQ scores [$F\ (2,38) = 0.53$, $p = .925$].

Based on their RSSQ scores, participants were further segregated into low and high susceptible groups using the cluster analysis procedure – Partitioning Around Mediods (PAM). The PAM function suggested that 13 participants comprised a lower susceptibility group and that the remaining 7 participants formed a higher susceptibility group. Taking susceptibility as a between-groups factor, the subsequent repeated-measures ANOVA revealed that the lower and higher susceptibility groups were significantly different from each other ($F(1,18)=52.101$, $p<0.001$). The interactions between SS susceptibility and FOV as well as SS susceptibility and motion frequency were both significant ($F(1,18)=4.03$, $p=0.05$; $F(2,36)=6.19$, $p=0.005$, respectively). This indicates that the two groups not only exhibited different SS levels but also showed significantly different patterns of SS responses across different FOVs and different motion frequencies.

Data for the high and low susceptibility groups are presented in Figure 4. Significant effects of visual motion frequency on SS were revealed from the data in high susceptibility group, where the RSSQ scores were different across different motion frequency conditions [$F\ (2,12) = 8.01$, $p = .012$]. The interaction between FOV and visual motion frequency was not significant [$F\ (2,12) = 0.49$, $p = .56$]. For the low susceptibility group, as expected, significant effects of visual motion frequency on SS were not found because these participants reported very little SS.

Discussion

The results of this experiment support the hypothesis that SS evoked using the scene motion would be distributed differently across different scene motion frequencies. Regression analysis of within-participants contrasts can help to reveal the possible quadratic effect of motion frequency on SS. Frequency is a quantitative variable that can be treated as a predictor for regression analysis. The 3 levels of motion frequencies used in this study - low (0.035 Hz), mid (0.080 Hz), and high (0.213 Hz) for 3 conditions were designed as equal intervals along the logarithmic scale. The results showed that the quadratic effect of motion frequency was significant [$F\ (1,6) = 7.19$, $p = .036$], indicating that the crossover hypothesis of SS distribution across different motion frequencies was supported by this experiment for high susceptibility participants. The mean RSSQ scores across different frequency conditions suggested that SS evoked using the scene motion in a mid-range frequency (around .07 Hz) was greater than that with higher or lower scene motion frequencies.

Regarding effects of FOV, this analysis also indicated that participants reported more SS symptoms with increasing FOV. With larger FOVs, participants were exposed to more visual flow in their peripheral visual field and this peripheral stimulation apparently contributes to their SS response. These results corresponded to previous studies which concluded that wide FOVs lead to greater visually-induced self-motion and postural disturbance [2].

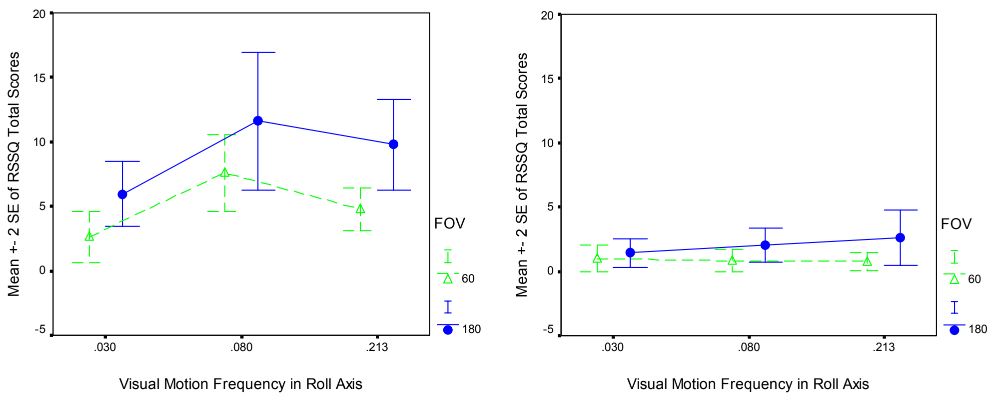

Figure 4. Effect of FOV and visual motion frequency on RSSQ scores. The left and right panels are data from the high and low susceptibility groups, respectively.

Significant interaction between FOV and visual motion frequency on RSSQ scores was not observed in this experiment. These results leave our hypothesis of the interaction, as showed in Figure 3, remaining as an open question. The statistical insignificance of the interaction could be due to the small effect sizes in this experiment. Increasing the sample size, especially including participants with more evident SS symptoms, could be one way to improve the study. Enlarging the intervals of the motion frequency levels could help to evaluate the hypothesized interaction between FOV and motion frequency.

The large variance of the SS responses in this study may be attributable to individual differences in SS susceptibility. Large individual differences also have been reported in numerous other studies (e.g. Park and Hu 1999, Yoo 2000,12].The fact that large simulator and motion sickness susceptibility individual differences occur in randomly selected participant populations supports the approach of segregating susceptible from non-susceptible participants for subsequent analysis. This seems especially appropriate for research designed to explore possible interventions to alleviate disturbance or sickness.

EXPERIMENT 2. SIMULATOR SICKNESS DURING REDIRECTED WALKING-IN-PLACE (RWP)

"Redirected Walking" is an interface technique designed to permit simulated walking in large virtual scenes [18,19]. There are many techniques that allow simulated locomotion in human-scale, immersive virtual scenes. These include flying with a joystick or other hand-controller [20], using a treadmill [1], walking-in-place where is user makes walking motions but keeps herself physically in the same spot [21], and leaning [15]. The choice of locomotion technique has been shown to affect the user's experience, sense of presence [22,24], and probably the level of SS, which is a serious problem for many users [10].

Real walking, where the user physically walks in the lab, and virtually moves the same distance and in the same direction though the VE, is better than flying with a joystick, or walking-in-place. One serious problem with real walking, however, is that the size of the virtual scene is limited by the size of tracked area or lab.

To address this limitation of real walking, Redirected Walking works by making the user turn herself by interactively and imperceptibly rotating the virtual scene around her. Under the right conditions, Redirected Walking would cause the user to unknowingly walk in circles in the lab, while thinking she is walking along a straight and infinitely long path in the virtual scene.

Even in labs which are too small to have the user imperceptibly walk in a full circle, Redirected Walking can still be employed, by forcing the user to look around at strategically placed waypoints in the virtual scene. While the user is rotating herself to look around, the system can inject substantially more rotational distortion without the scene rotation being perceived. The virtual scene is rotated so that a direction which was previously out of tracker range is now safely within the lab. The distance between adjacent waypoints must be less than the length of the tracking area. Figure 5 illustrates the use of waypoints.

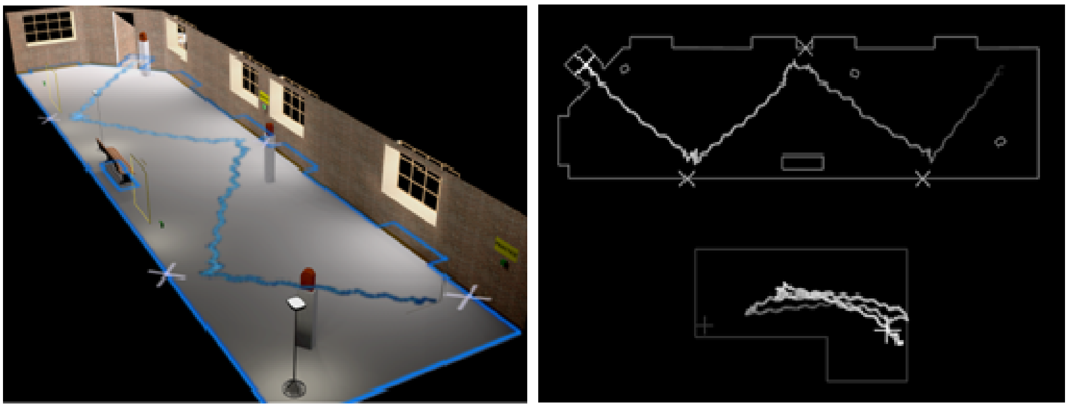

Figure 5– left: "brick room virtual scene. right: overhead views of the path in virtual scene (above) and in the real lab (below) drawn to scale. As the user zigzagged through the virtual scene, she unknowingly walked back and forth between the ends of the lab instead.

Redirection can be applied to locomotion in surround-screen VE systems such as CAVES® and CAVE-like systems, if combined with walking-in-place. In many VE systems, if a user wishes to move toward an object in the virtual scene, she first rotates the virtual scene, using a hand-controller (e.g., joystick), so that the virtual object is in front of her. Data from a preliminary study showed a positive correlation between a user's sense of presence and physically turning her body (to face a virtual object) instead of turning the world with a joystick [22,19]. With Redirected walking-in-place (RWP), the goal is to allow the user to turn in the VE by turning her body instead of using a joystick (or other hand-controller).

The problem with turning the body, however, is the vast majority of CAVEs have only three vertical walls (6). If the user turns her body, she will eventually face the open back wall. The RWP procedure slowly and imperceptibly rotates the virtual scene, while the user is walking-in-place, so that the user is made to turn towards the front wall of the CAVE without noticing. While standing in one place and turning her head to look about the virtual scene, the system scales the rotation so that she can see more of the virtual scene before turning so far that she sees the open back wall.

The goal of the RWP is to allow participants to virtually walk, even in complete circles, through a virtual scene presented in a CAVE and never see the open back wall. RWP works by interactively and imperceptibly rotating the virtual scene about the participant. This rotation causes the user to continually turn towards the front wall of the CAVE (Figure 7). Experiment 2 compared RWP with the traditional interface in which the user turns using a hand-controller.

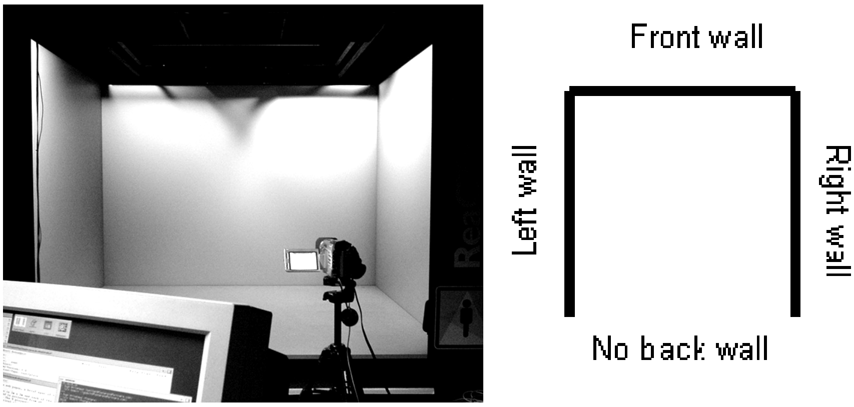

Figure 6 – left: a CAVE with an open back wall (with the virtual scene turned off). right: an overhead diagram of the same CAVE.

Method

Participants

Data from 28 people were collected in this experiment. They were randomly assigned to the control or experimental group. Participants were asked to carry out a task in a virtual scene. The control group turned in the virtual scene using a hand-controller. The experimental group turned in the virtual scene by rotating their torsos during RWP. Both groups completed the same task in the same virtual scene and both used walking-in-place to move forward. The redirection algorithms are presented in [18,19].

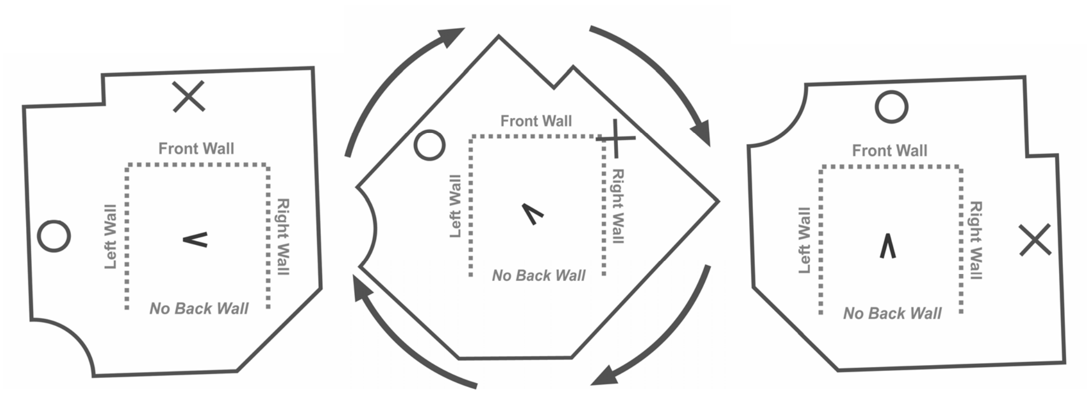

Figure 7 – illustration of how RWP works. Left: the user (the arrow head in the center) turns to face the target circle; Center: the system responds by slowly turning the virtual scene to the right. Right: the target circle is then behind the front wall.

Apparatus

The system used in this experiment was a Trimension ReaCToR™ with four projection surfaces (three vertical walls and the floor). A SGI Onyx2, using four graphics pipes (one per screen) and 5 processors, generated imagery at 22.5 frames per second for each eye. Participants wore Crystal Eyes™ shutter glasses to view sequential stereo imagery. The refresh rate of the four cathode ray tube (CRT) projectors was 90 Hz (45 Hz in each eye). An Intersense™ IS-900 tracker provided the position and orientation of the participant's head and torso at 180 Hz. The IS-900 wand, which is normally held in the user's hand, was attached to the participant's waist with a hip-worn camera bag to track the participant's torso orientation. For the hand-controller condition, participants use a Logitech™ wireless computer mouse. In the control condition where the participant turned using the mouse, pushing the right button rotated the virtual scene to the right, and pushing the left button rotated the virtual scene to the left. Both groups of participants wore the same equipment, even though the hand-controller was not used by the participants in the RWP condition. When the system detected that the participant was stepping, it moved the viewpoint in the virtual scene in the direction in which her torso was pointing.

Procedure

The virtual scene was the brick room (Figure 5). The VE included four yellow signs: "Alarm", "Halon", "Practice" and "Window". Participants were asked to find, walk up to, and read all four signs, then to revisit them in alphabetical order. This task forced the participant to walk about and explore the large virtual room and was specifically designed to involve many substantial changes of direction. Before beginning the task, participants were familiarized with the VE equipment and practiced walking-in-place. Participants made walking motions (lifting the legs) but stayed on the same the spot physically. The VE system detected this motion and moved her forward in the virtual scene [23]. During RWP, the virtual scene slowly and imperceptibly rotated so that the participant was made to turn toward the front wall of the CAVE without noticing. While the standing in one place and turning her head to look about the virtual scene, the system scaled the rotation so that she could see more of the virtual scene before turning so far that she saw the open back wall. The total virtual scene exposure duration was approximately 10 min.

Both experimental and control group participants filled out the Simulator Sickness Questionnaire (SSQ) [7] immediately before and after their experimental session. (The SSQ was designed for use only after the VE exposure. It was administered before the VE exposure only to detect participants who did not meet the requirements for completing the experiment.)

Results

The mean SSQ scores were 18.0 ± 21.7 for the control group (who used a hand-controller to turn) and 9.5±6.9 for the RWP group. Note that the mean scores for the hand-controller-turning group were higher than for the torso turning group. Furthermore, the 75th percentile scores (the criterion Kennedy proposed in the original SSQ paper [6]) for the hand-controller-turning group were higher than for the torso turning group (Figure 8). This suggests RWP with torso turning resulted in less SS than using a hand-controller to turn in the VE. In summary, users did not notice the rotations of the virtual scene and RWP did not measurably increase SS.

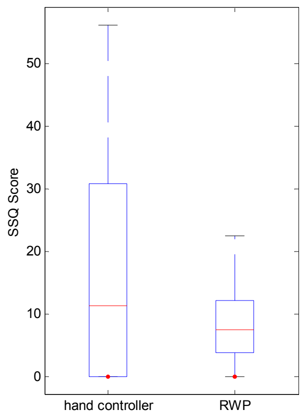

Figure 8. Box and Whisker plots of SSQ scores. The plot shows the distribution of total SSQ scores. The 75th percentile of the total SSQ score for Redirection is less than that for turning with a hand controller.

Discussion

Contrary to expectations from several colleagues, RWP with torso turning did not signficantly increase SS compared to using a hand-controller to rotate the visual scene. In fact, it reduced it. Based on 75th percentile scores, SS was less for the group using RWP and torso turning (Figure 8).

Why Redirection alleviates SS

As noted previously, this work was pursued within the framework of the cue conflict theory, which suggests that simulator and motion sickness are a consequence of conflicting motion cues from the visual and vestibular self-motion systems. Based on previous research, recommendations for alleviation of SS include: (1) limit simulated self-motion in the visual – inertial "cross-over" range, around 0.07 Hz [4]; (2) provide motion prediction cues [13]; and (3) present an independent visual background – IVB [12,16,17].

Regarding recommendation 1 and as noted previously, the visual and vestibular systems are sensitive to different frequencies of motion. One approach used in RWP to minimize both the participants' SS and their awareness of scene rotation was to keep the rotations of the virtual scene at as low a frequency as practical. The goal was to keep scene rotation below the visual-vestibular crossover frequency, thus minimizing the conflict between visual and vestibular cues. As discussed above, previous research showed that differing visual and vestibular cues (i.e. the visual cue is from one motion path and the vestibular cue is from another) are more likely to cause sickness when those cues are in a frequency band where both the visual and vestibular self-motion systems are highly responsive. If the cues are in a frequency range where either channel is unresponsive, there is less conflict and less sickness.

Regarding recommendation 2, studies undertaken by Lin *et al*. [11,13] indicate that SS and motion sickness may be significantly reduced by cues that permit participants to predict up-coming scene motion. Active movement during RWP -- walking and turning the head and torso – provide excellent prediction cues as indicated by von Holst and Mittelsteadt's reafference model [25]. Use of the hand-controller to turn in the VE is an unnatural locomotion procedure; consequently, more SS should be reported when using the hand control to turn in the VE because less salient prediction cues would be provided.

Regarding recommendation 3, IVB studies suggest that SS is reduced when the spatial reference frames provided by the visual scene and the inner ear vestibular receptors are congruent. During torso turning in the VE, virtual scene rotation is congruent with inertial rotation detected by the vestibular semicircular canals. When turning is mediated by a hand controller, scene moment is incongruent with semicircular canal signals.

In conclusion, statistical analysis does not permit demonstration that RWP does not increase simulator sickness compared to real walking (without using Redirection or any other form of virtual rotation) because a reasonable estimate of standard deviation in SSQ levels is lacking. But, compared to the alternative (virtual rotation controlled by the user), RWP with torso turning appears to result in less SS. RWP with torso turning apparently does not unacceptably increase the level of SS.

CONCLUSIONS

Findings from two experiments are reported. Experiment 1 examined effects of FOV and visual motion frequency on SS. Experiment 2 addressed SS during redirected walking-in-place (RWP). Experiment 1 provided direct support for the crossover hypothesis, which suggests that restricting simulated motion frequency in the range where conflicting motion cues to the visual and vestibular self-motion systems are readily detected (around 0.07 Hz) should reduce SS. Experiment 2 procedures were developed based on the crossover hypothesis and results were consistent with expectations based on it.

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