Virtual Guiding Avatar: An Effective Procedure to Reduce Simulator Sickness in Virtual Environments

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ABSTRACT

This study developed a new procedure, a Virtual Guiding Avatar (VGA), which combined self-motion prediction cues and an independent visual background (IVB) to alleviate simulator sickness (SS). The VGA, which was embodied as an abstract airplane, was designed to lead the participant along a horizontal motion trajectory through a virtual environment. Both motion prediction cues and IVBs, which provide an earth-fixed reference frame, reduced SS in separate previous studies. Participants were exposed to complex visual motion through a cartoon-like simulated environment in a very wide field of view driving simulator. Participants' responses to avatars with varying motion properties – fixed, rotation only or rotation plus translation – were assessed using a within-subjects experimental design. Results indicated that SS was reduced by a VGA that presented rotational cues alone or rotation plus translation. The VGA also increased participants' sense of presence and enjoyment relative to conditions lacking a VGA. The VGA procedure can be used to enhance user experiences in immersive virtual environments as well as to improve motion simulator design.

Author Keywords

Motion prediction, simulator sickness, prediction, avatar, virtual environment

ACM Classification Keywords

H.5.2 Information interfaces and presentation (e.g., HCI): User interfaces.

INTRODUCTION

The widespread problem of virtual environment-induced sickness, which is similar to simulator sickness (SS), has been addressed by several investigators [1,13,15,29]. Following the sensory conflict theory, SS is thought to be the result of conflicting motion and orientation cues from the visual and vestibular receptors [7,24]. When the environment is altered such that conflict between visual and inertial orientation cues arises, as occurs in many virtual environments and motion simulators, SS may result.

Development of effective procedures to alleviate SS have been pursued extensively at the Human Interface Technology Laboratory [2,3,19,20,23]. The major purpose of this study was to evaluate a new procedure designed to reduce SS in virtual environments while preserving participants' sense of presence and enjoyment. We called this procedure – a Virtual Guiding Avatar (VGA). The VGA combines the ideas of motion path prediction cues and an independent visual background (IVB). The avatar guides the participants through virtual environments. Effects of the VGA on SS, presence, and enjoyment were evaluated in this study.

The Role of Prediction in Virtual Environments

Drivers or pilots who control vehicle motion rarely exhibit sickness symptoms even though they may report sickness when they are passengers [26]. In virtual environments and motion simulators, interactivity between users and virtual environments has been reported to significantly affect SS [17,28]. Participants who controlled simulated motion reported fewer SS symptoms. User control correlates with sickness during both real and virtual motion. These findings are consistent with reafferent feedback models developed by Helmholtz [10], Sperry [27], von Holst and Mittelstaedt [11] and Held [9]. These models suggest that voluntary movement initiates perceptual processes that differ from those associated with passive movement. Similar models incorporate feedforward mechanisms for prediction of self-orientation and self-motion information. Simulated motion predictability due to active control may be a key factor contributing to SS reduction.

Our previous studies assessed the hypothesis that predictability during passive simulated motion may reduce SS. Using a driving simulator, which included a full size vehicle, SS scores were recorded from subjects who actively controlled the simulated motion versus those who were passive observers. One of the passive conditions included prediction cues by showing the path trajectory on the 'ground' of the simulated environment. As expected, active control resulted in less SS. More interesting was the observation that the condition with path prediction cues significantly reduced the SS reported by the participants. Adding the element of predictability (following the path trajectory) during passive travel through the virtual

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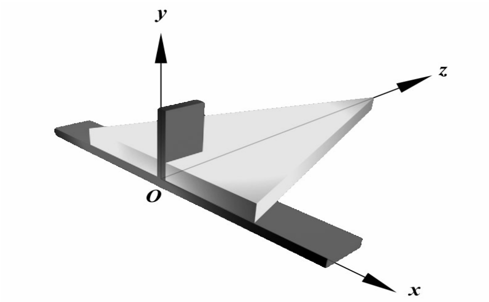

Figure 1. Design of the Virtual Guiding Avatar.

environment resulted in lower reported SS relative to the condition without prediction cues.

These data are consistent with anecdotal reports of motion sickness in cars. Motion sickness-prone riders prefer to sit in the front seat. This could reduce motion sickness in two ways. First, visual cues that conflict with those from the vestibular receptors would be reduced because less of the visual field (the inside of the car) indicates the passenger is stationary. Second, riding in the front seat permits looking ahead, predicting turns. Our previous results as well as the anecdotal reports from drivers and passengers suggested the intervention to alleviate SS during passive motion through a virtual environment described in this study.

The Independent Visual Background (IVB)

Prothero [22] suggested that an understanding of motion sickness in virtual environments and motion simulators could be facilitated by considering "rest frames." A rest frame can be defined as the particular reference frame used by an observer as the basis for spatial judgments, as what should be regarded as "stationary." Based on this construct, Prothero proposed a procedure for reducing the sickness and balance disturbance associated with exposure to motion simulators and virtual environments. A visual scene can be divided into two components, one labeled the "content of interest" and another called the IVB [23]. Based on the cue conflict approach to simulator and motion sickness [7], an IVB could provide visual motion and orientation cues that match those from the vestibular receptors. Consequently, inclusion of an IVB in a virtual environment could reduce simulator and virtual environment sickness. Several previous studies, including one presented at the CHI2001 conference, supported the hypothesis that the inclusion of an inertially stationary IVB in a fixed-base virtual environment reduced SS and balance disturbance evoked by visual scene motion [2,3,23].

The Virtual Guiding Avatar (VGA)

The VGA was designed to combine the concepts of an IVB and of un-obtrusive prediction cues. The VGA is an object that "leads" the participant along a motion trajectory through the virtual environment, similar to drivers following a car in front of them along a winding road. This VGA was represented as an abstract airplane. The 3D data, structure and design of the airplane, were implemented in C++ using the OpenGL Library and run on a Silicon Graphics computer.

Figure 2. Snapshot of the VGA in the Crayoland virtual environment presented in a driving simulator. The VGA hovered centrally in the middle of the screen and faced the upcoming direction. The lower part of the snapshot is a reflection of the scene on top of the vehicle in the simulator. Subjects sat in the driver's seat during the experiment.

Design of the Avatar

When designing the avatar, we evaluated whether the algorithm scales worked well as the complexity of the 3D environment and, consequently, the number of polygons, increased. To do so, we tested the airplane in different 3D environments and lighting conditions. Since our design required only a few semi-transparent triangles, the performance and frame rates were not affected by virtual environment complexity.

The abstract airplane had a triangular yellow body, a rectangular horizontal orange wing and a rectangular vertical orange tail, as shown in Figure 1. The airplane was 3 feet long, 2.4 feet wide (from the back wing extreme left to extreme right), and 0.45 feet high (the vertical tail). It was rendered in an absolute earth-fixed coordinate system (O, x, y, z); therefore, as the 3D environment moved, the airplane was not directly affected by the motion of the scene. As illustrated in Figure 1, the origin, O, of the earth fixed coordinate system (O, x, y, z) was centered on the lower back end of the vertical tail. The axis Oz, was perpendicular to the screen plane, Ox was parallel to the raster lines, and Oy was perpendicular to the plane (O,x,z). The airplane hovered centrally, in the middle of the screen, facing the forward direction (straight ahead), as shown in the snapshot of Figure 2.

Motion of the Avatar

The airplane was controlled by six functions: a roll function that rotated it around Oz, a yaw function that rotated it around Oy, a pitch function that rotated it around Ox, a forward translation function that translated it along Oz, a sideways translation function that translated it along Ox and a height adjustment function that translated the airplane along Oy.

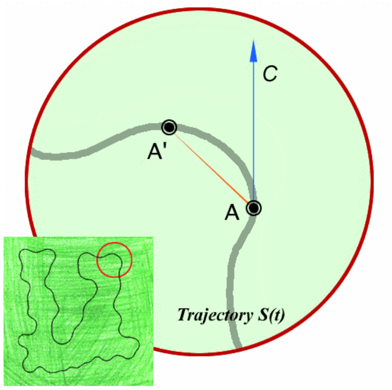

Figure 3. Design of the of the VGA's motion. The lower-left panel illustrates a bird's eye view of the path layout in the virtual environment. The black curve on the lower-left panel indicates the motion trajectory that subjects traveled along in the experiment. A portion of the trajectory is magnified as shown in the large circle. Point A represents the current location of the subject's eye point; point A' indicates the location of the subject's eye point after a short time period, Δt; the vector AC, which illustrates the direction the subject currently faces, is tangent to the trajectory at point A.

The subject followed a parameterized trajectory S(t), where t was time. If the eye point of the participant were at point A at current time t, (see Figure 3), they would be facing the direction of the vector AC, which is tangent to the trajectory at point A. Point A' is the position of the eye point at time t+Δt.

Δt is a time interval which represents the lead time of the eye point that will move from point A (current location) to A' in Δt sec. Research by Hallett [8] suggested that the normal response latency between the visual stimulus motion and the eye movement response is around 500 milliseconds. Thus, the lead-time, Δt, was chosen to be 500 milliseconds.

To provide a cue for predicting motion, the yaw and/or roll and/or sideways translation functions were applied to the airplane to indicate that the trajectory was going to turn left in Δt seconds. The yaw, roll and translation values were proportional to the signed angle CAA', as illustrated in Figure 3.

Questions and Hypotheses

The following questions and hypotheses addressed effects of a VGA on SS during passive travel through a virtual environment. Does an earth-fixed avatar reduce SS? We hypothesized that it would reduce SS because it works as an IVB. Does an earth-fixed avatar that rotates reduce SS? We hypothesized that the earth-fixed rotating avatar would reduce SS because it both works as an IVB and provides motion prediction cues. Does a non-earth-fixed avatar that rotates and translates reduce SS? We hypothesized that the non-earth-fixed rotating and translating avatar would reduce SS because it provides redundant motion prediction cues. Finally, we predicted that the presence of a avatar would enhance presence and enjoyment based on our observation during pilot studies.

METHOD

Subjects

12 subjects, 8 women and 4 men, ages 18 to 35, 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-to-normal vision. Subjects were paid $15 for participating in the experiment. An additional 25 cents was awarded for each correctly answered memory question. The protocol was approved by the University of Washington Human Subjects Review Committee.

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 were 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 forest. Additional software permitted inputs and replay of prerecorded trajectories through Crayoland. The computer-generated images were presented on the 3 screens as a panoramic scene and subtended a 220º horizontal field of view. The scene was presented in stereo using CrystalEyes stereo glasses (StereoGraphics Inc.) that alternatively masked the left and right lenses. Subjects sat in the driver's side of the car on a wooden plate that replaced the driver's seat. The experimental environment is illustrated in Figure 4.

Procedure

Subjects were "driven" through the Crayoland virtual environment along a quasi-circular trajectory that included left and right turns (yaw movements) as well as forward translation. Identical pre-recorded 120-sec trajectories around the virtual environment were presented in all experimental conditions. The motion frequency in the yaw axis varied throughout each trial, yet the trajectory remained the same across all conditions. Using a within-subjects experimental design, each subject was exposed to each of the 4 experimental conditions – Condition 1, no VGA (control condition); Condition 2, an earth-fixed VGA without cues for turns prediction; Condition 3, an earth-fixed VGA that used rotation to provide cues for predicting turns; Condition 4, a non-earth-fixed VGA that used both rotation and translation to provide cues for predicting turns. Both magnitude of translation and lateral motion were determined by the angle calculated in Figure 3. All subjects experienced all 4 conditions. A memory task, which

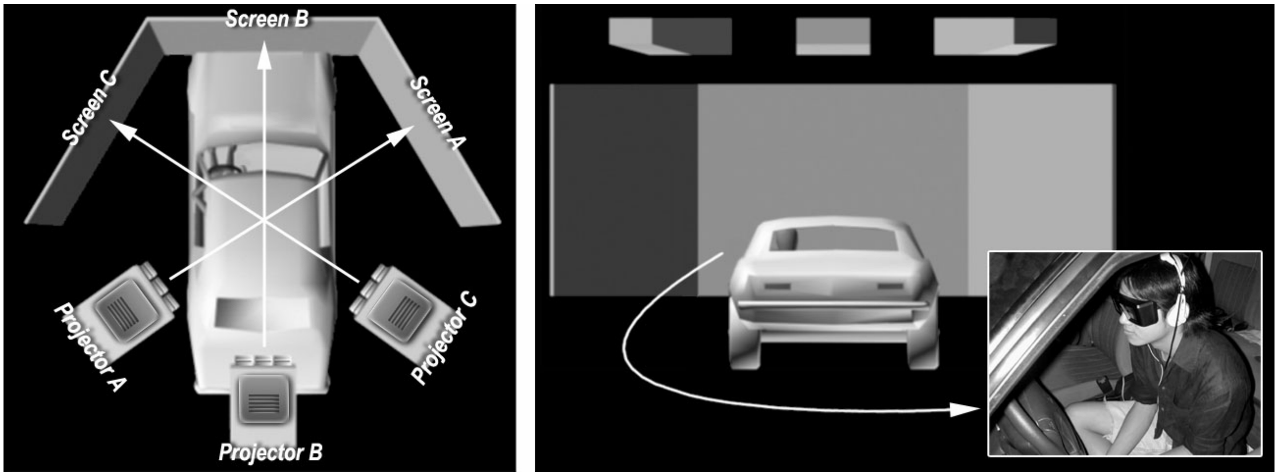

Figure 4. Experimental setting. The left figure shows a bird's eye view. The right figure shows a back view of the set-up as well as a close-up view of subject's position in the experiment.

required subjects to attend to various objects in Crayoland, was conducted for each condition. The experiment sequence was as follows.

1. Pre-test procedures included instructions and a pre-test Revised Simulator Sickness Questionnaire [14]. The Revised Simulator Sickness Questionnaire uses many items from the widely known Simulator Sickness Questionnaire [12], employs a slightly different scoring procedure, and adds a Strain/ Confusion Subscale.
2. Four 120-sec experimental trials. Following each trial, subjects repeated the Revised Simulator Sickness Questionnaire and an Enjoyment, Engagement, and Immersion Questionnaire [18,20]. Rating methods including a series of multivariate approaches and the Item Response Theory are elaborated upon in the Human Interface Technology Laboratory technical report [21]. Subjects rested at least 5 minutes between trials. The rest intervals were prolonged as needed to maintain a low pre-trial SS level. The questionnaire was designed to access the experience of enjoyment, engagement, and immersion after virtual environment exposure. 14 Likert-scale questions and a memory test were included in the questionnaire. Based on these data, overall standardized scores for each of the 2 subscales, Presence and Enjoyment, were calculated.
3. Post-experiment comparisons. Subjects were asked to order the 4 trials they had just experienced based on their perception of (1) smoothness of the trajectory, (2) sharpness of turns, and (3) their ability to predict turns.

Subjects were randomly assigned, without replacement, to 1 of the 24 orders of the 4 experimental conditions. Each experiment took about 1.5 hours.

RESULTS

Repeated measures analysis of variance (ANOVAs) were calculated to examine the effects of the VGA on the Revised Simulator Sickness Questionnaire and The Enjoyment Engagement and Immersion Questionnaire. Diagnostic tests for the ANOVAs were performed to examine the normality and homogeneity of variance assumptions. Based on the normal quantile-quantile plots, the residual plots, and the Levene's test of equality of error variances, a logarithmic transformation of the Revised Simulator Sickness Questionnaire scores was performed to satisfy the assumptions of the analyses.

In terms of responses to the Revised Simulator Sickness Questionnaire, the scores were significantly different across the 4 experimental conditions [F(3,33)=6.395, p=.002]. Mean Revised Simulator Sickness Questionnaire scores for Conditions 1 – 4 are 7.95, 5.11, 2.58, and 3.11, respectively. The corresponding scores to Kennedy's well known Simulator Sickness Questionnaire are 36.01, 19.75, 9.76, and 10.97 [14]. Tests of within-subjects contrasts comparing Conditions 2 – 4 to the control condition (Condition 1) showed that Revised Simulator Sickness Questionnaire scores in Conditions 3 and 4 were both significantly lower than those in Condition 1 [p=.009 and p =.004, respectively]. However, Revised Simulator Sickness Questionnaire scores in Condition 2 were not significantly lower than those in Condition 1 [p=.107], although mean score differences in the expected direction can be clearly observed in Figure 5. This suggests that the VGA procedure can significantly alleviate the SS symptoms associated with simulated movement through a virtual environment.

In terms of responses to the Enjoyment, Engagement and Immersion Questionnaire, the repeated measure ANOVAs showed that the Presence Subscale scores were significantly different across the 4 experimental conditions [F(3,33)=6.205, p=.002], as were the Enjoyment Subscale scores [F(3,33) =5.918, p = .002]. Tests of within-subjects contrasts showed that the Presence Subscale scores in Condition 3 and Condition 4 were both significantly higher than those in Condition 1 [p=.030 and p=.030,

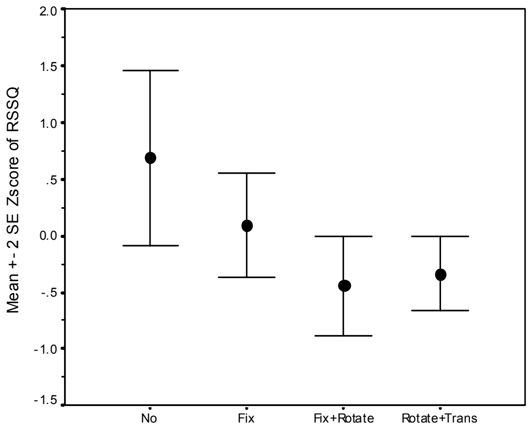

Figure 5. Revised Simulator Sickness Questionnaire scores as a function of condition. "No" (Condition 1): no VGA; "Fix" (Condition 2): earth-fixed VGA; "Fix+Rotate" (Condition 3): earth-fixed VGA coupled with rotational cues; 'Rotate+Trans' (Condition 4): non-earth-fixed VGA coupled with rotational and translational cues. Higher simulator sickness scores represent more simulator sickness.

respectively]. Similarly, the Enjoyment Subscale scores in Conditions 3 were significantly higher than those in Condition 1 [p=.028]. However, neither the Presence Subscale scores nor the Enjoyment Subscale scores in Condition 2 significantly differed from those in Condition 1. Interestingly, this result indicates that an earth-fixed VGA that incorporates rotational cues for predicting turns is likely to increase the sense of presence and enjoyment participants experience while they passively travel through a virtual environment. These results are summarized in Figures 5 and 6.

Comparing Condition 3 with Condition 2 revealed additive effects of rotational cues on an earth-fixed avatar. The post-hoc pairwise comparison showed that an earth-fixed avatar with rotational cues reduced SS scores significantly [p=.030]. Moreover, both Presence and Enjoyment Subscale scores in Condition 3 were significantly higher than those in Condition 2 [Presence: p=.050, Enjoyment: p=.018]. This suggests that the additive effects of the rotational prediction cues on an earth-fixed avatar also enhanced subjects' sense of presence and enjoyment.

Based on ordinal data collected in the post-experiment debriefings regarding participants' perception of self-motion, a Friedman Analysis of Variance by Ranks showed that reports of "perceived sharpness of turns" was significantly different across the 4 conditions [$\chi^2(3)=9.092$, p=.028]. The ranking data suggest that perceived sharpness of turns in the condition with no VGA was greater than in the other conditions. In Condition 3, where rotational cues were coupled with the earth-fixed avatar, the turns were perceived as less sharp than in the other conditions, as shown in Figure 7.

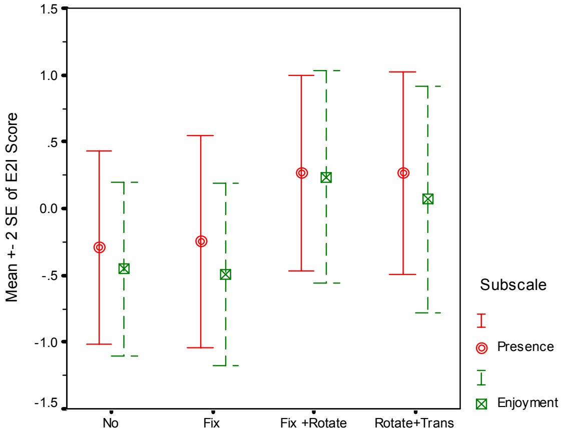

Figure 6. Scores on Presence and Enjoyment Subscales as a function of condition. "No", "Fix", "Fix+Rotate", and "Rotate+Trans" represent Conditions 1 to 4 as described in Figure 5. Higher E^2I scores represent higher levels of enjoyment and presence.

The reported ability to predict turns differed marginally across the 4 conditions [$\chi^2(3)=6.926$, p=.074]. For the Conditions 3 and 4, which provided prediction cues, participants reported they had a greater ability to predict turns than for Conditions 1 and 2. The mean ranks of perceived smoothness of the trajectory generally showed a trend opposite to that for perceived sharpness of turns. However, the data did not reach a statistically significant level of .05 [$\chi^2(3)=4.394$, p=.222]. The mean ranks suggested that trajectories in Conditions 3 and 4 were likely to be perceived as smoother than the other 2 conditions.

DISCUSSION

The effects of a VGA on SS reduction during passive travel through a virtual environment were most significant when the VGA was coupled with turns prediction cues. Our results suggest that the non-earth-fixed rotating and translating avatar reduced SS because it provides redundant turns prediction cues. Finally, the results also indicate that the senses of presence and enjoyment increased in the conditions where the turns prediction cues were provided by the VGA.

VGA: Prediction cue properties

The results suggest that the VGA can significantly reduce SS symptoms when cues for motion prediction are provided by in the avatar. These results support our hypothesis that visual cues that permit prediction of upcoming motion direction can significantly alleviate SS during passive travel through a virtual environment. When the avatar assumes the role of a guide, it indicates future motion direction shortly before the scene actually moves. This provides a small time window between the motion of the avatar and the motion of the entire scene. Fitts and Posner [5] considered the limitations of a human operator tracking dynamic

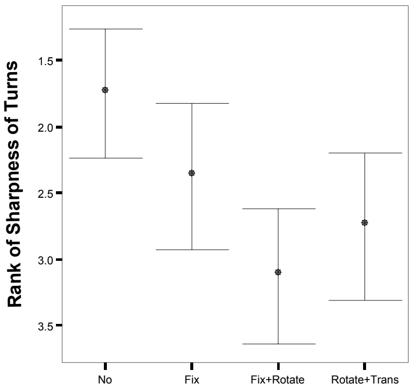

Figure 7. Ranks of perceived sharpness of turns as a function of condition. 'No', 'Fix', 'Fix+Rotate', and 'Rotate+Trans' represent the Conditions 1 to 4 as described in Figure 5. We reversed the vertical axis for illustrative purposes. Since this graph illustrates ranked data, the smaller number represents a higher level of sharpness reported by subjects.

signals. They suggested that anticipating the time of arrival of the signal might reduce a large portion of the processing delay. Having the capability to (consciously or unconsciously) predict the motion direction before the scene actually moves, may better prepare virtual environment participants for the upcoming disturbance.

Responses to perceived motion questions support similar conclusions. Subjects reported self-motion perception along the trajectory to be "least sharp" in conditions 3 and 4. This suggests that the prediction cues from the VGA contribute to the perception of smoother turns; i.e., reduced disturbance may be interpreted by the subject as smoother turns. Reduction of perceived disturbance may also explain the reduction of SS symptoms when the VGA permitted prediction.

What is the underlying mechanism that makes us "prepare" for upcoming change in the environment before the change actually occurs? What allows us to compensate for anticipated disturbance? The SS reduction associated with prediction cues may be understood in terms of compensation based on feedforward cues. Von Holst and Mittlesteadt's reafference principle [11] describes feedforward cues as being related to two classes of problems: perceptual stability and compensation for disturbance. A key component of their model is an "efferent copy" of the efferent command to initiate movement. Comparison of the efferent copy with movement-induced change of the afferent signal (reafference) from a receptor such as the eye, provides the information required to determine whether changes in the afferent signals result from an external disturbance or the observer's own activity.

While passively traveling through a virtual environment, the activation of the feedforward mechanism may possibly contribute the reduction of retinal slip. This reduction may be associated with the reduction of SS. Turns prediction permitted subjects to maintain gaze in the direction of the car's heading. This may have reduced the retinal slip, which causes blurring of the visual scene. Similar retinal slip produced by panning a scene with a video camera is frequently reported to be disturbing. Examining and comparing eye movement for the 4 conditions may provide further evidence for this suggestion.

We were concerned that reduction of SS may be primarily associated with the VGA being a distraction from the scene motion. Four reasons suggest that this is not the case. First, if the VGA worked as a distracter, we would expect performance on memory questions to suffer in the trials in which it was present. However further analysis of the results indicated that there were no significant differences in performance on the memory test portion of the Enjoyment, Engagement, and Immersion Questionnaire across the 4 conditions. Second, presence scores in Conditions 3 and 4 were another indicator that the avatar was not primarily a distracter. In these conditions, presence scores were higher than in Conditions 1 and 2. If the avatar were distracting the subjects away from the scene, we would expect them to be less engaged in the virtual environment content and consequently report less presence. Third, SS symptoms were reported after exposure to the virtual environment when the avatar was not present. Numerous anecdotal reports indicate that SS may increase rapidly when a task is completed. A similar increase in SS would be expected if the avatar were a distracter. Finally, we recently conducted a follow-up study to look at the correlation between eye movements and scene motion across these same 4 conditions. Preliminary results also suggest that the SS reduction is not directly related to the avatar being a distraction. If the avatar were a distracter, we would expect the correlation between scene motion and eye movement to decrease in Conditions 3 and 4. The overall correlation between scene motion and eye movements increased when the avatar provided turns prediction cues. This provides further evidence that the VGA did not primarily function as a distracter.

VGA: IVB properties

The VGA in Conditions 2 and 3 played the role of an IVB. A SS reduction purely from the earth-fixed avatar in Condition 2 (functioning as an IVB) did not reach a statistically significant level although a mean difference in the expected direction can be observed in Figure 5. This may be due to the perception of induced motion of the earth-fixed avatar. For instance, consider a visual "frame" such as a rectangle, with an earth-fixed ball inside of it. When the frame moves to the right, people usually report that the earth-fixed ball has moved to the left. The illusory motion of the ball is called induced movement [4]. It is most pronounced when the frame and ball are at the same distance from the observer. The relative location of the frame in the visual field (peripheral versus central) is another critical factor [6]. Relative to the entire visual scene, the avatar was very small, which made the likelihood of motion induction of the avatar high. Furthermore, the avatar, which was designed as an abstract airplane, was meant to be interpreted as a flying or moving object. This earth-fixed avatar played a very different role from a stationary "background" IVB examined in our previous studies. Additionally, 8 of the 12 subjects perceived that the avatar was 'flying or running" in Condition 2. Influences of perceived motion of an earth-fixed grid IVB induced by visual movement were examined by Lin et al. [19]. Lin suggested that the effectiveness of the IVB decreases when motion induction of the IVB occurs. This may explain why the stationary earth fixed VGA in Condition 2 did not result in lower SS scores.

VGA: Effects on Presence and Enjoyment

Interestingly, this VGA procedure also enhanced levels of presence and enjoyment subjects reported when the rotational cues were coupled with the earth-fixed avatar. The avatar may play the role of a 'mediator', enhancing the cognitive interaction between viewers and the visual scene. Regenbrecht and Schubert's model [25] suggested that the presence of an avatar in virtual environments increases interaction possibilities and thus increases the sense of spatial presence. This may explain the increased levels of presence and enjoyment when the avatar was present. The guiding avatar might also facilitate subjects' participation or direct subjects' attention into the visual scene. Lee, Sheldon, and Turban [16] suggested that mental focus refers to the degree to which the user was able to concentrate and become absorbed in an activity. They addressed the role of mental focus in predicting enjoyment and performance and found that mental focus was positively related to both enjoyment and performance. Considering participants' exposure to a virtual environment, they could just passively sit and do nothing but observe, or they could more actively perform certain tasks such as driving along a route in the virtual environment. Passively observing versus actively driving in a virtual environment may have involved different degrees of mental focus, and consequently led to different degrees of enjoyment during the virtual environment experience. It would be interesting to further explore the mechanisms underlying increased presence and enjoyment in the trials for which the VGA provided prediction cues.

CONCLUSION AND FUTURE WORK

The leading avatar was embodied as an abstract airplane and situated in the virtual environment scene. Presenting the Crayoland virtual environment in a very wide field of view driving simulator, we conducted an experiment using a within-subjects design to evaluate the effect of this new VGA procedure. In different conditions, the VGA exhibited different motion properties – earth-fixed, earth-fixed and rotation only, or non-earth-fixed with rotation plus translation. We developed this new VGA procedure to enhance user's experiences in virtual environments by significantly reducing the pervasive side effects, SS, during human-virtual environment interaction. By providing self-motion prediction cues, this VGA procedure allowed users to predict oncoming direction of simulated motion and to compensate for disturbance. It also added the IVB element, which visually provides self-motion and self-orientation cues that match those from the vestibular receptors.

The results indicated that SS was significantly reduced either by a VGA that was earth-fixed and coupled with rotational prediction cues or by a non-earth-fixed VGA that provided rotational and translational prediction cues. Interestingly, the VGA also enriched the positive aspects of user experiences in a virtual environment – participants reported more presence and enjoyment relative to conditions lacking a VGA.

The significant SS reduction associated with motion prediction cues provided by the avatar may be understood in terms of compensation based on feedforward mechanisms. The ability to predict upcoming motion may permit subjects to maintain gaze at the center of radial visual flow, i.e., in the direction of the car's heading. Preliminary examination of eye movements supports this suggestion. Finally, the enhancement of presence and enjoyment by the guiding avatar needs further investigation to allow us to explore its potential.

This newly developed VGA procedure can be used to enhance user experiences in immersive virtual environments as well as to improve motion simulator design.

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