User Experience Modeling and Enhancement for Virtual Environments That Employ Wide-Field Displays

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Abstract. User experience in virtual environments including presence, enjoyment, and Simulator Sickness (SS) was modeled based on the effects of field-of-view (FOV), stereopsis, visual motion frequency, interactivity, and predictability of motion orientation. We developed an instrument to assess the user experience using multivariate statistics and Item Response Theory. Results indicated that (1) presence was increased with a large FOV, stereo display, visual motion in low frequency ranges (.03 Hz), and high levels of interactivity; (2) more SS was reported with increasing FOV, stereo display, .05-.08 Hz visual motion frequency, lack of interactivity and predictability to visual motion; (3) enjoyment was increased with visual motion in low frequency ranges (.03 Hz) and high levels of interactivity. The resulting response surface model visualizes the complex relationships between presence, enjoyment, and SS. Overall, increasing interactivity was found to be the most profound way to enhance user experience in virtual environments.

Keywords: user experience modeling, virtual environment, presence, simulator sickness, enjoyment, interactivity.

1 Introduction

The assessment of user experience in virtual environments (VEs) has been primarily focused on evaluating the sense of presence reported by users while in VEs. Virtual presence is defined as being the extent to which participants feel they are in a place away from their actual physical setting while experiencing a computer generated simulation [1]. This is considered to be a product of a VE's immersive properties [2]. Previous studies suggested that VEs that produce an increased sense of immersion or effectively direct users' attention towards certain tasks would produce higher levels of presence. It is generally noted that experiencing presence requires focus on a meaningfully coherent set of stimuli in the VE to the exclusion of unrelated stimuli in the physical location. A number approaches have been demonstrated to be effective for the enhancement of virtual presence, such as increasing FOVs of VE displays and visually inducing self-motion perception of VE users.

Applying these approaches for presence enhancement in VEs, unfortunately, could also increase the likelihood for their users to develop symptoms similarly to those in motion sickness. The phenomenon of VE induced sickness, or simulator sickness

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(SS), has affected a great number of the users that it has become a focal point of discussion and research during the past two decades [3][4]. Referring to former studies in motion sickness, the sensory conflict theory has been widely used as the explanation for the development of SS symptoms in VEs. According to the sensory conflict theory, SS is thought to be the result of conflicting motion and orientation signals from the visual and vestibular senses [5][6], as in a VE the self-motion perception induced by the visual cues is expected to be deviated from that suggested by the cues from the vestibular receptors. While a user experiences SS in a VE, s/he could develop a number of symptoms such as increasing salivation, sweating, nausea, fatigue, dizzy, headache, eyestrain, blurred vision, difficulty focusing, and difficulty concentrating. Although the symptoms could vary upon individuals, a prolong accumulation of SS severity could often make the users feel uncomfortable and even withdraw from a VE exposure. Consequently, this side-effect could contribute negatively to user experience, and may also impact the sense of presence or enjoyment in a VE. For instance, the development of presence could be interrupted because of difficulty focusing on the visual scenes or tasks, whereas the level of enjoyment could sink due to general physical discomfort.

The use of VE technology is at the core of many games and other entertainment platforms. A major goal of the entertainment-based VEs is to deliver the experiences to the user in a more engaging and fun way. Unlike presence and SS, degree of enjoyment users experience in a VE has not yet been widely studied. Various factors that influence degree of presence and SS in a VE system may affect degree of enjoyment in similar or different ways. In addition, user experience regarding enjoyment might be impacted directly by the level of presence and/or SS a user experienced. Nichols et al. [7] studied relationships among presence, enjoyment, and SS during exposure to a VE. They hypothesized that subjects who enjoyed participating in the VE would report higher presence and lower SS. The results from this study suggested that presence added to the enjoyment of the VE and that there was no significant correlation between SS and enjoyment. However, another study described in a doctoral thesis found a negative correlation between SS and enjoyment [8]. Unpacking their hypothesis, it seemed to imply enjoyment as a mediator between VE attributes and presence or SS. Their results, nevertheless, seemed to reveal that enjoyment would be affected by presence or SS. This indicates that enjoyment could be associated with presence and SS, however, the underlying model and possible causal relationships among them need to be examined.

Furthermore, although degree of enjoyment is likely to be associated with the presence or SS that users experience in a VE, enjoyment may not just simply be a product of presence and/or SS. Various factors of a VE system could contribute to enjoyment independently of their influence on presence and SS. Planteb et al. [9] studied if virtual reality technology enhances the psychological benefits of exercise in a laboratory setting. Their results suggested that pairing VE with exercise enhances enjoyment, and reduces tiredness compared with VE or exercise alone. This study implied that coupling certain tasks in a VE was likely to increase level of enjoyment. In a VE requiring performance of certain tasks or activities, participants needed more mental focus. Lee et al. [10] examined the influence of mental focus on performance and enjoyment on students' course work. 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 VE, they could just passively sit and do nothing but observe, or they could more actively perform certain tasks such as driving through a route in the VE. Passively observing versus actively driving in a VE involved different degrees of mental focus, and consequently led to different degrees of enjoyment during the VE experience. This led to a very interesting avenue for our research – exploring the effects of interactivity on enjoyment in a VE.

In summary, the sense of presence and SS have been considered as crucial aspects of users' responses in VEs; enjoyment should also be a crucial aspect to study since it could be particularly of interest to the VE-based entertainment applications. While studying user experience in a VE, we consider presence, SS, and enjoyment should be assessed simultaneously, in particular that numerous inter-correlations among presence, SS and enjoyment could exist. In addition, many studies have looked into the approaches of tuning VE variables (e.g. FOV of VE displays) to enhance the sense of presence. It is likely that factors that enhance presence might also impact the level of enjoyment and/or SS. It is therefore important to study both of the more positive aspects, i.e. presence and enjoyment, and the aftereffect, i.e. the SS, together when investigating the approaches of using different variables to enhance user experience in a VE. The objective of this research was to gain a deeper understanding of those relationships among presence, enjoyment, and SS, and seek to model user experience in a VE in a more systematic and holistic fashion. Furthermore, through the development of the model we hope to discover the approach of best tuning the VE variables, which will ultimately enhance user experience as a whole. In terms of the positive aspects of user VE experience, we hoped to find approaches to enhance presence and enjoyment and diminish SS; whereas in terms of aftereffect of user VE experience, we aimed to find approaches that alleviate SS while at the same time preserving presence and enjoyment.

2 Development of Assessment Tool

As discussed above, the levels of presence, enjoyment, and SS are the primary aspects for assessing user experience in VE in this research. Regarding the measurement of SS, the Simulator Sickness Questionnaire (SSQ) developed by Kennedy provides information to distinguish the multiple dimensions of the sickness including nausea, disorientation and oculomotor disturbance [11]. SSQ has been generally used as the instrument to monitor or assess the SS symptoms participants may develop in VEs and motion simulators. Our research used SSQ or Revised SSQ (RSSQ) [12], which is a variation of SSQ, to assess the user experience concerning SS. Regarding the measurement of presence and enjoyment, as there are no universally accepted measure techniques for presence and enjoyment in VEs, by referring to previous researches and consolidating the instruments from other studies, we developed a refined scale – the Enjoyment, Engagement, and Immersion Scale (E^2I Scale) to assess user experiences in VEs.

2.1 The E^2I Scale

Engagement and immersion are two elements that contribute to the idea of presence. Following Witmer and Singer's [2] approach to the concept of presence, engagement indicates the degree to which the subjects' attention is directed to the VE, similar to when one is engrossed in a novel or movie. Immersion is defined as the experience that one is wrapped in a surround, similar to being inside an elevator. Enjoyment is the feeling of pleasure or contentment during the VE experience. The Enjoyment, Engagement and Immersion Scale, or the E^2I Scale, was developed to assess enjoyment, engagement, and immersion experienced by participants in a VE.

Development of the scale began with the creation of Likert-scale (7-point) questions. Each question was considered an item in the construction of the scale. To examine engagement and immersion, 9 items were developed and modified based on the well-known presence questionnaires described by Singer and Witmer [13] and by Slater et. al [14]. These items were constructed based on the ideas of engagement (EG) and immersion (IM) associated with the concept of presence. These 9 items and their associated ideas were as follows. (Crayoland is the name of the VE used in the experiments.)

Q1. *How much did looking at Crayoland (the VE) involve you; i.e., how much did the visual scene attract your attention? (EG)*
Q2. *To what extent did events such as noise occurring outside Crayoland distract your attention from Crayoland? (EG)*
Q3. *How compelling was your sense of objects moving through space? (EG, IM)*
Q4. *How consistent were experiences in the virtual environment; i.e., to what extent did you feel as though you were actually moving through Crayoland? (EG, IM)*
Q5. *How completely were you able to actively survey or search the environment using vision? (EG, IM)*
Q6. *Were you involved in the memory task to the extent that you lost track of time? (EG)*
Q7. *How much did you have a sense of "being there" in the virtual environment? (IM)*
Q8. *During the time of the experience, which was strongest on the whole, your sense of being in the driving simulator room or in Crayoland? (IM)*
QMem. *A set of questions to assess structure of memory. (EG, IM)*

The enjoyment component of the E^2I Scale was based on the attributes of pleasure (PL) and satisfaction (SF) during a VE experience. The 5 enjoyment items were as follows. The item "QTime" was added to the questionnaire as the 15th item for the later experiments.

Q9. *To what degree did you feel unhappy when the experience was over? (PL)*
Q10. *How much did you enjoy yourself during the experience? (PL, SF)*
Q11. *Would you like to repeat the experience you just had? (SF)*
Q12. *How interesting was your experience in Crayoland? (PL)*
Q13. *How much would you be willing to pay to have a similar experience? (PL)*
QTime: *Circle the amount of time you estimate the experience you just had took.*

A unique feature of the E^2I Scale design was the memory test (QMem) embedded in the questionnaire. Previous research has suggested that the degree to which a subject memorizes the features in a VE may be an indicator of how "present" the subject is, and could therefore be useful in measuring presence. The memory structure for a VE was suggested to include the six dimensions [15] – types of objects, shapes, colors, relative locations, relative sizes, and event sequences. In our study, each of the six dimensions of the subjects' memory structure of the VE was assessed by a specific type of questions concerning the attributes of the dimension [16].

2.2 The Refinement of E^{2}I Scale

Evaluation of the E^{2}I Scale involved (1) using factor analysis to detect the underlying structure and extracting factors, (2) selecting and weighing items for each factor based on their contributions using reliability tests and some multivariate approaches, (3) examining the item qualities including discrimination power and location for each factor, and finally (4) developing overall index for each factor as a subscale based on the analysis of Item Response Theory (IRT). Two subscales – the Presence and Enjoyment Subscales were constructed in the E^{2}I Scale. Based on the responses to the items, standardized Z scores provided an index to indicate the levels of presence or enjoyment.

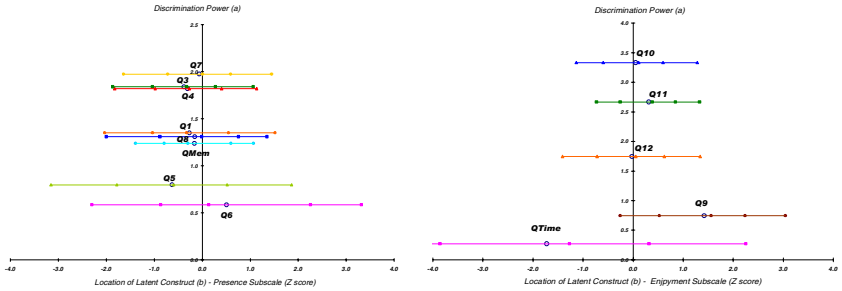

Fig. 1. The discrimination powers against the locations and thresholds from the ITR analyses for the 8 items in Presence Subscale (left panel) and Enjoyment Subscale (right panel)

Figure 1 (left) illustrates the qualities of the items in the Presence Subscale from the analysis of IRT, based on the discrimination power axis relative to the location axis for each item. The figure indicates that items Q7, Q3, and Q4 had greater discrimination powers than the others. Interestingly, both Q3 and Q4 were items related to vection (visually induced self-motion perception). This seems to suggest that degree of vection should be a significant indicator for assessing the degree of presence that a user experiences in a VE. The item Q7, which directly asked about the degrees to which a subject had a sense of "being there" in a VE, also appeared to have a greater capability for discriminating responses on presence, based on the response patterns from the data. On the other hand, the Item Q6 seemed to be less sensitive for discriminating presence. Item Q6, which asks about the degree to which subjects "lost track of time", had a higher location on the Presence Latent Construct. This suggests that as users approach a higher presence level they gradually lose their ability to keep track of time. The implications of the results provided a deeper understanding and suggested possible approaches for refining the items in the Presence Subscale.

The qualities of the items in the Enjoyment Subscale are illustrated in Figure 1 (right), which similarly indicates that item Q10 had greater discrimination powers than the other items. Item Q10, which directly asked about the degree of enjoyment experienced in the VE, had the greatest capability for discriminating levels of enjoyment. Item Q9, which at the end of each trial asked about the feeling of "unhappiness" due to the VE experience terminating, exhibited a higher location on

the Enjoyment Latent Construct. This implies that the user needs to approach a higher level of enjoyment in order to feel unhappy when the VE experience has terminated. The QTime item does not appear to be sensitive enough to reflect the difference of subjects' enjoyment experience. Part of the reason may be because subjects had differing estimates of how much time they spent in the VE, despite the fact that the stimuli were identical. Subjects may also have had difficulty in specifying the number of seconds in a given time period without being presented with a reference time period. In other words, it could be easier for the subjects if there is a time period being presented as a baseline, and they could do direct magnitude estimation of the target time period. The IRT results suggest the future refinement of this item. Again, these analyses provide a deeper understanding and suggest possible approaches for refining the items in the Enjoyment Subscale.

3 Experiment Settings

A Real Drive driving simulator (Illusion Technologies International, Inc.) including a full-size Saturn car (General Motors Company), three 800 x 600 pixel Sony Superdata Multiscan VPH-1252Q projectors, and 3 230 x 175 cm screens was used to display the VE for the experiment. The 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. Participants sat on the driver's seat of the car and wore the CrystalEyes stereo glasses (StereoGraphics Inc.) while moving through the Crayoland VE along a trajectory that included left and right turns (yaw movements) as well as forward translation. A number of variables including image characteristics (such as FOV and stereoscopic depth cues), visual motion frequency, interactivity, and visual cues or intervention for motion prediction were manipulated in a series of 6 experiments as listed in Table 1. The effects of the variables on presence, enjoyment, and SS were measured in all of 6 experiments using E^2I and SSR/RSSQ. The experiment environment is illustrated in Figure 2 and the details of the experiments can be found at [16][17][18][19][20].

Table 1. A list of independent variables applied in the 6 experiments included in this study

Exp. ID	Independent Variable	# Conditions	# Participants
4.1	FOV	4	10 (5W, 5M)
4.2	Stereo	4	10 (4W, 6M)
4.3	Visual Motion Frequency	6	20 (11W, 9M)
5	Interactivity	4	12 (5W, 7M)
6	Visual Cues for Motion Prediction	3	12 (7W, 5M)
7	Virtual Guiding Avatar (VGA)	4	12 (8W, 4M)

4 Results and Discussion

The results from the Experiments 4.1, 4.2, 4.3, and 5 showed that manipulation of those VE variables (i.e. FOV, stereo, visual motion frequency, and level of interactivity) can significantly contribute to the positive aspects of user experience,

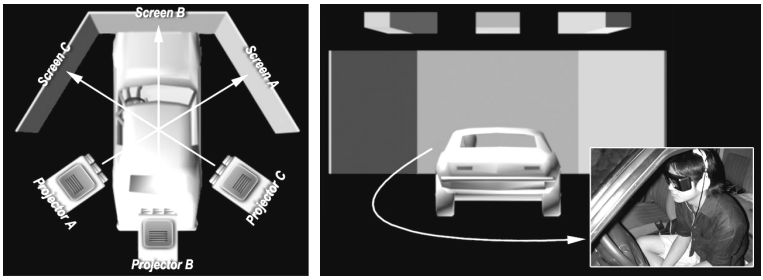

Fig. 2. Equipment setting. The left panel shows a bird's eye view. The right panel shows a back view of the set up as well as a close-up view of subject's posture in the experiment.

including presence and enjoyment. These factors, however, also have significant negative impact on user experience. In addition, new approaches to alleviating SS were developed and then tested in Experiments 6 & 7. These approaches using visual interventions in the VE scenes were demonstrated to be effective for SS reduction. The impact of the use of these approaches on presence and enjoyment was measured during the experiments, in order to evaluate the potential side-effects of using these visual intervention techniques on the positive aspects of user experience. Several findings derived from these experiments can be applicable as design implications for enhancing user experience in immersive display systems.

4.1 Enhancing Presence and Enjoyment

Figure 3 (left) illustrates that the sense of presence in a VE is significantly associated with FOV, stereopsis, visual motion frequency, and levels of interactivity. It suggests that a VE with the following four attributes is likely to make a more compelling user experience as a result of higher levels of presence: (1) large FOV (i.e, 180°), (2) visual scene presented in stereo, (3) visual scene moving at a very low frequency (i.e., 0.03 Hz, and (4) an active mode of interaction with the visual scene. Figure 3 (right) indicates that the degree of enjoyment in a VE is significantly associated with visual motion frequency, levels of interactivity, and use of visual interventions. It suggests that a VE with the following three attributes is likely to make a more interesting user

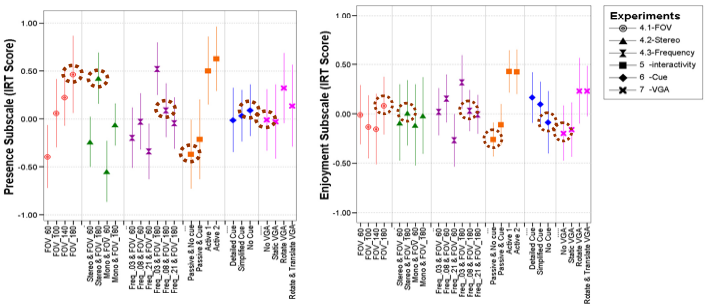

Fig. 3. Responses on Presence (left) and Enjoyment (right) Subscales

experience, resulting from a higher degree of enjoyment: (1) a visual scene moving at a very low frequency (such as 0.03 Hz), (2) an active mode of interaction with the visual scene, and (3) the use of visual interventions to alleviate SS.

Manipulating theses factors would vary the resulting levels of presence or enjoyment in a VE. A practical question to look into is which factors have large effects than the others. Across the 6 studies, a common condition bearing similar properties was included in each experiment, as identified in circles in Figure 3. These properties included a 180° FOV, stereo graphics, 0.05~0.08 Hz continuously oscillating visual motion, subjects in passive mode, and no visual intervention for SS alleviation applied. Considering these common conditions into the same baseline level, the results imply that levels of interactivity play a key role in enhancing both presence and enjoyment. It has become clear that when participants have active control of a VE, the degree of presence they experience as well as the enjoyment level could be higher than when the other factors were manipulated. In addition, FOV also makes a significant contribution in levering the degree of presence. However, when the FOV reaches its ceiling (full-coverage FOV: about +/- 110° from the center of a visual field), providing active control of scene motion will have a great influence on participant's sense of presence in a VE.

4.2 Reducing the Aftereffect – SS

Figure 4 (left) indicates that SS induced in a VE is significantly associated with FOV, stereopsis, visual motion frequency, levels of interactivity, and the ability to predict upcoming motion. It suggests that SS could be reduced in an immersive display system bearing the following attributes: (1) a small FOV (such as 60°), (2) visual scene not presented in stereo, (3) visual scene moving at a very low frequency (such as 0.03 Hz), (4) allowing VE users to be in an active mode interacting with the visual scene, and (5) using visual interventions to provide predictive cues for upcoming motion. Similarly, taking the common conditions into account, the overall trend again suggests that levels of interactivity play a significant role concerning SS induction in a VE. When users have active control of scene motion, the degree of SS reduction is larger than when varying the levels of the other factors. Since having control over the scene motion implies having the theoretical capability of being able to predict upcoming visual motion, two kinds of visual interventions were developed to alleviate SS: unobtrusive prediction cues and the VGA. However, these procedures were not as effective as directly providing the active control of scene motion. The figure also indicates that decreasing FOV or having low frequency visual scene motion would also reduce the degree of SS.

4.3 Enhancing User Experience as a Whole

As noted above, the three primary aspects of user experience in a VE – presence, enjoyment, and SS could intimately link and may be correlated with one another. In order to seek for the approaches to enhance user experience as a whole, it is important to use a more holistic approach to further demonstrate the relationships among the three aspects in relation to these VE variables used in the experiments. Using a response surface based on a nonparametric smoothing density estimation of

Enjoyment Subscale scores by SSQ and Presence Subscales scores, the resulting response surface model, as illustrated in Figure 4 (right), visualizes these complex relationships. It suggests four properties that concern correlations between presence, enjoyment, and SS: (1) a positive correlation between presence and enjoyment, (2) a negative correlation between SS and enjoyment, (3) no specific correlation between presence and SS, and (4) either a decline in presence or a growth in SS resulting in a decrease in enjoyment.

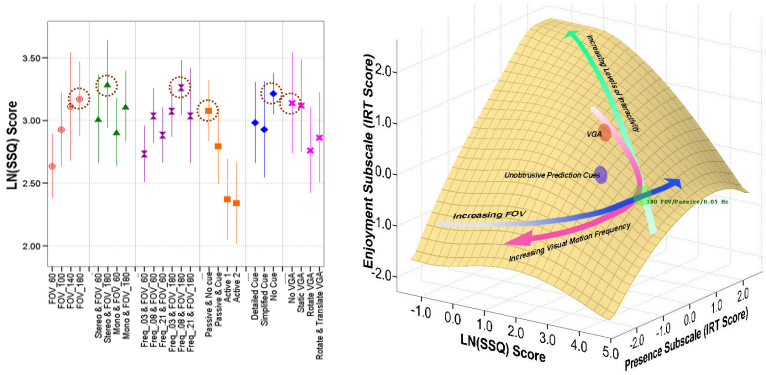

Fig. 4. Responses on SSQ (Left). The right panel shows a response surface model summarizing the overall trend of the effects of different factors on presence, enjoyment and SS.

Based on this construct, we summarize the following practical design implications for enhancing user experience in VEs:

- Increasing level of interactivity in a VE is the most profound way of enhancing the overall user experience of all factors examined in this dissertation. It leads to a high degree of presence and enjoyment as well as a low degree of SS.
- Visual motion frequency influences user experience in a complex way. If possible, it is useful to decrease the frequency when the visual motion is around .05 to .08 Hz. As the frequency of visual motion is above the .05 to .08 Hz rage, the higher the frequency, the lower the resulting presence and SS will be.
- Visual interventions for motion predictions may enhance user experience. Both approaches in this study effectively reduced SS. A VGA type of intervention may be more effective in enhancing user experienced and might increase presence.
- FOV has a significant impact on both presence and SS. However, varying the FOV does not have a great effect on enjoyment. As indicates in the figure, increasing FOV leads to an increase in both presence and SS. SS causes the overall user experience to decrease. In Figure 3 (right), the relatively flat effect on enjoyment across different FOV also reflects this finding, where enjoyment level remained similar when FOV was the major factor being manipulated.

The model presented in Figure 4 (right) clearly summarizes the findings across the different studies described in this paper. The effects of FOV, visual motion frequency, interactivity, and visual interventions on presence, enjoyment and SS are visualized.

This model represents an overall trend in the findings. Further studies are needed to investigate the effects regarding detailed variations within each factor as well as the interactions among these factors.

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