COMPARISON OF SIMULATOR SICKNESS USING STATIC AND DYNAMIC WALKING SIMULATORS

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Findings from the Simulator Sickness Questionnaire (SSQ) evaluated several factors related to the physiological effects of immersive virtual environments (IVE) exposure. Subjects conducted locomotion activities within a selected IVE by traversing a three-dimensional computer hallway setting using either a mouse-driven static simulator or a treadmill-operated dynamic simulator system. Two levels of rendered visual detail were also compared for their SSQ effects. Simulator Sickness Questionnaire analyses reveal an effect of gender such that the females were significantly more affected by simulator activities than the male subjects. Length of time in the simulator was also found to have a significant physiological effect on the participants in the tested range of 13-23 minutes of exposure. Longer time intervals were associated with significantly greater symptoms of simulator sickness and perceived discomfort. A comparison of scores between distance judgment and movement production activities produced no significant results, leading to the conclusion that the task objectives were not different from one another in simulator effects on the participants. Individuals who used the static simulator were significantly more affected than those with similar exposure times in the dynamic simulator. Analysis of two levels of detail in the IVEs revealed a tendency for more richly textured imagery to yield higher Total Severity SSQ scores with nearly significant differences. In accordance with previously established simulator sickness profiles, the static simulator pattern of symptoms resembled those of visually-dependant IVEs (cybersickness), while the dynamic simulator symptomology was more analogous to that of motion-based IVEs (classic simulator sickness).

INTRODUCTION

Simulator sickness (SS), or cybersickness, is a by-product of high fidelity visual simulators and virtual interfaces. SS resembles the more familiar malady of motion sickness, including, but not limited to pallor, dizziness, headache, and nausea (Kennedy et al., 1993). While many of the manifestations of simulator sickness and motion-induced sickness are similar, the severity and incidence of SS symptoms tend to be lower than those of motion-related discomfort, but still significant in many cases. In addition, the emerging combination of symptoms of simulator sickness follows a pattern that is distinguishable from typical travel-induced motion sickness (Stanney et al., 1997).

Simulator sickness is an important consideration in evaluating the viability of an immersive virtual environment. SS can vary along two dimensions, the extent of the symptoms and the combination of symptoms (Kennedy et al., 1992; Kennedy et al., 1993; Stanney et al., 1997). These two dimensions are computed as *Total Severity* scores and *Subscale* measures, respectively. This paper primarily addresses the effect of various factors on Total Severity measures. The three Subscale categories of nausea, oculomotor disturbance, and disorientation are also discussed in terms of their pattern of occurrence for static and dynamic simulator systems.

Past research and general reporting have found that women tend to be more susceptible to simulator sickness than men. Higher occurrences of reported sickness in females have been documented using data from commercial transport records and in studies with large sample sizes (Kennedy et al., 1995). Biocca (1992) states that women report a more intense perception of motion discomfort and simulator sickness symptoms even though their sensory responses do not differ from those of men experiencing the same conditions. Other research found that while females had consistently higher mean simulator sickness scores than did males, the results did not differ at the .05 level of significance (Kolasinski & Gilson, 1998; Rich & Braun, 1996).

It has also been shown that prolonging the duration of simulator immersion tends to result in an increase in the perceived negative physiological effects (Kennedy et al., 1999; McGee, 1998; Stanney & Kennedy 1998). This has been consistently supported for exposure durations up to approximately 30 minutes, beyond which evidence of adaptation has been demonstrated (McCauley & Sharkey, 1992; Stanney & Kennedy, 1998).

Little research has directly compared simulator sickness outcomes by level of visual detail in a virtual environment or between static and dynamic simulator systems. A dynamic simulator system is defined to be one in which the participant performs a physical activity that provides locomotive energy to move through the immersive virtual environment. A static simulator system requires no whole-body movement or significant physical effort by the operator. A computer mouse (or hand-controlled device) provides the primary method of advancement in a static IVE.

Simulator sickness and visually-induced motion sickness are hypothesized to arise from a lack of parity between the sensory experiences and expectations (Knerr et al., 1998; Hettinger & Riccio, 1992). It is hypothesized more visually complex simulations may contribute to perceived discomfort. It is also predicted that a subject's locomotor control (in this case walking) in the 3-D environment and the subsequent kinesthetic, proprioceptive, tactile, and vestibular sensory feedback will result in a reduction in simulator sickness outcomes.

METHODOLOGY

Participants

Sixty subjects (18 females and 42 males) participated in the IVE locomotion study. They ranged in age from 18 to 40 years of age and had 20/20 or corrected to 20/20 vision. All subjects were paid a $10 honorarium for participating in the full set of activities. All subjects completed the study.

Apparatus

Static and dynamic walking simulators were constructed to provide two different modes of IVE locomotion. Identically rendered 3-dimensional corridor settings were traversed in each simulator system. As seen in Figure 1, while standing in place and viewing the virtual hallway through a head mounted display (HMD), subjects controlled locomotion in the *static simulator* via the left mouse button. Pressing the button resulted in traversing the virtual environment at a normal walking pace.

Figure 1. Subject navigating in the static simulator.

A manually-powered treadmill was used as the mode of locomotion in the *dynamic simulator*. Subjects viewed the hallway scene through the HMD and controlled the rate of advancement by varying their walking cadence on the treadmill (Figure 2). The dynamic treadmill system with accomodating velocity would update the viewed scene in response to the operator's gait activity.

Figure 2. Subject navigating in the dynamic simulator.

Procedures

Following completion of preliminary forms and the Preimmersion SSQ Checklist, subjects were given instructions and practice opportunities with their respective simulators. Then the participants engaged in estimation sessions for either a distance judgment (DJ) or movement production task (MP). Each simulator estimation session consisted of two runs of ten trials each as follows:

For the distance judgment task objective, the subject was instructed to travel an unknown distance, and for each trial, a computer signal indicated when to stop advancing. Depending upon the simulator system, the subject could halt locomotion by releasing the left mouse button or by pausing on the treadmill At the stopping point, the subject provided a verbal estimate of the distance that was just traversed. The distance judgment value was recorded to a data file by the experimenter. This was repeated for 10 randomly-ordered trials within a run. Each subject experienced either the static or dynamic simulator and viewed either plain surfaces with gradient line *visual cues* or richly *textured* simulated scenes.

For the movement production task, participants were instructed to travel a specified distance. Subjects advanced in the IVE until they perceived that the requested distance has been traversed. Depending upon the simulator mode of locomotion, advancement could be voluntarily halted when the subject released the left mouse button or stopped walking. The traversed distance was then written to a data file. This sequence was repeated for 10 trials of different distances within each of the 2 runs.

During practice sessions, subjects were initially instructed to learn a benchmark distance called the Standard Unit (SU). Although the distance was not revealed to the subjects, the Standard Unit was in actuality a 20-foot length. This standardization allowed all participants to refer to the SU as a common metric for estimation purposes and required no experiential knowledge of other distance metrics, such as feet or meters (Waller, 1999).

In each practice session, a subject was given five trials to learn the SU. After the practice session, a run of ten trials was conducted. In each run, a subject traveled 10 different distances, which were multiples and fractions of the Standard Unit, ranging incrementally from 0.5 to 5 SU (10 to 100 ft). This set of distance segments is similar to the one used in the estimation task of the Virtual Environment Performance Assessment Battery, which ranged incrementally from 9 to 100 feet (Lampton et al., 1994).

As described, distances were either or verbally estimated or traversed, depending upon whether the task objective was distance judgment or movement production, respectively. To vary the order of distances to be traveled or estimated, subjects were randomly assigned to a series. Each series contained all 10 distances, with the order rearranged for each set.

The Simulator Sickness Questionnaire as developed and described by Kennedy et al. (1993) was used as the primary assessment tool. Preimmersion SSQ measures were collected before simulator exposure and Postimmersion SSQ measures were collected following the simulator sessions using the SSQ checklist of symptoms. In addition, SSQ Score Differentials were calculated by subtracting Pre-Exposure scores from the associated Post-Exposure scores to document any change in a subject's physiological status that may be due to simulator involvement. The effects of gender and duration of exposure were evaluated by examining Total Severity measures. The main effects of (1) activity (distance judgment or movement production), (2) mode of locomotion (static or dynamic simulator), and (3) level of visual detail (gradient lines or textured polygons) were investigated using the SSQ Total Severity Differentials and the Post-Exposure scores for the 60 subjects.

RESULTS

T-test analyses of the Preimmersion Total Severity SSQ scores for the male and female subjects showed that pre-exposure scores did not differ significantly by gender. However, there was an effect of gender for post-exposure Total Severity scores at $p<.005$ and for the Total Severity Differential at $p<.01$. Post-Exposure Total Severity averages were 23.27 (s=9.48) for females and 15.94 (s=8.67) for males. The mean Total Severity Differentials equaled 17.45 (s=8.88) for female subjects and 11.40 (s=7.70) for male participants. Refer to Figure 3 for the comparisons and values for these metrics. Note that the females also reported higher preimmersion baseline symptoms, but that they were not significantly more severe than those of the males.

Initiatory analyses revealed that there was no significant effect of activity (task) on SSQ scores. With no differences in duration of exposure for the two task objectives, distance judgment and movement production activities yielded statistically similar Postimmersion Total Severity scores and Pre-Post Differentials. The mean DJ Total Severity SSQ was slightly higher at 15.9 (s=7.47), while MP averaged 14.6 (s=8.57). The mean DJ and MP Differentials were identical at 10.29 (s=7.06) and (s=7.47) for DJ and MP, respectively. In addition, no interaction effects involving the activity factor were significant.

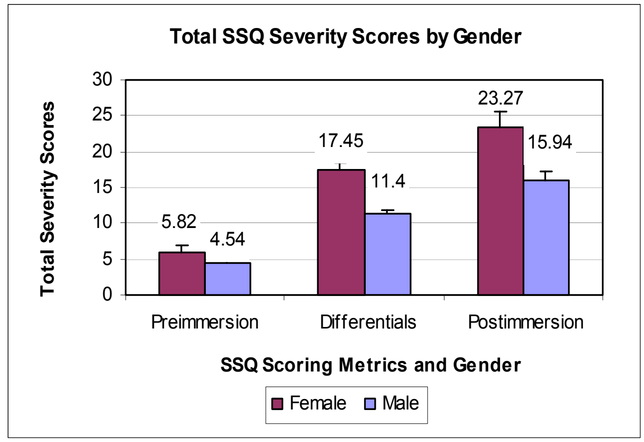

Figure 3. SSQ Total Severity scores by gender. Means and standard error bars are displayed.

ANOVA was used to assess the effect of exposure duration on SSQ scores among time interval delineations of (1) 15 minutes or less, (2) 16-20 minutes, and (3) greater than 20 minutes (Figure 4). Bonferroni post-hoc analyses revealed significant differences among all Postimmersion group means at the $p<.01$ level. The same results were found for the Total Severity Differentials ($p<.02$), indicating that longer exposure durations had a significant influence on intensifying perceived discomfort in the time ranges tested.

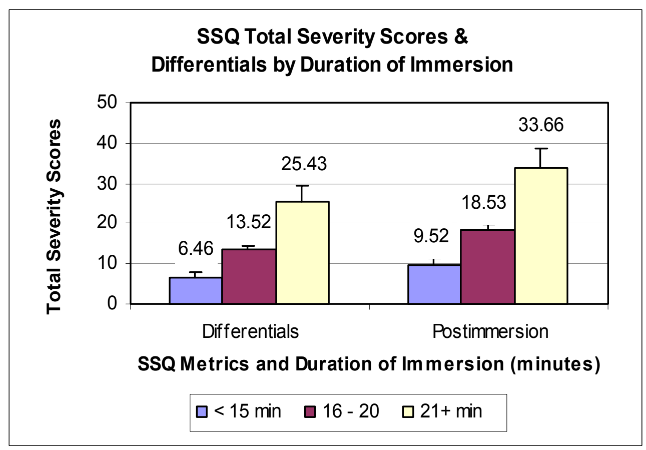

Figure 4. SSQ Total Severity scores by duration of exposure. Means and standard error bars are displayed.

Total Severity SSQ responses were analyzed for differences between the two levels of visual detail in the immersive virtual settings. For subjects who experienced the more richly detailed textured environment, Pre-Post Total Severity Differentials were higher at 15.33 (s=7.88) than for those who viewed the plain imagery with ground surface gradient lines, averaging 11.10 (s=8.65). The Differentials by detail were nearly significant at p=.06. Similarly, the Post-Exposure averages were higher for the textured level of detail but were not found to be significant (p=.12). Groups viewing the more photorealistic texture scenes scored 20.07 (s=8.76), while the groups experiencing the plain surfaces with gradient line cues averaged 16.21 (s=9.89) on the Post-Exposure Total Severity measures. Figure 5 depicts the tendency for the textured detail to yield higher SSQ scores.

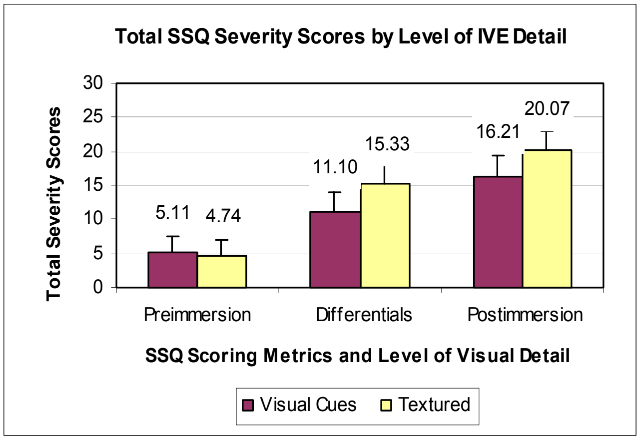

Figure 5. Effect of simulator detail on SSQ Total Severity scores. Means and standard error bars are displayed.

Using independent *t*-tests, mode of locomotion (as defined by type of simulator) was found to have a significant effect on simulator sickness. Note that there were no differences in Pre-Exposure scores or in duration of immersion across the conditions. However, subjects using the static locomotion simulator had symptoms that were significantly more acute than those operating the dynamic locomotion simulator. This outcome is evidenced by the highly significant differences found in the Postimmersion Total Severity Scores (p<.001) and in the Pre-Post Total Severity Differentials (p<.001). The Postimmersion Total Severity Score averaged for 23.94 the static simulator (s=9.74) and only 15.24 and for the dynamic simulator (s=7.96). Mean Differentials were 19.07 and 10.29 for the static and dynamic simulators, respectively. These outcomes are shown in Figure 6.

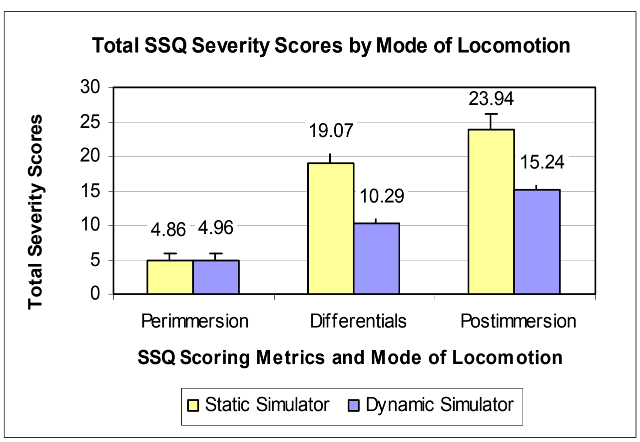

Figure 6. Effect of locomotion mode on SSQ Total Severity scores. Means and standard error bars are displayed.

Finally, analyses were conducted on the incidence, severity, and combination of the Subscale categories of nausea (N), oculomotor discomfort (O), and disorientation (D) for the two types of simulators The Subscale patterns revealed markedly different profiles for the static and dynamic and simulators. Figures 7 and 8 present the subscale profiles and scores for the Pre-Post Differentials and for the Post-Exposure scores, showing consistent patterns across the categories for each training environment.

The profile that emerged for the *static* simulator system was D > O > N. That is, symptoms of disorientation were greater than oculomotor symptoms which were more prominent than nausea. This differs slightly from the pattern found by Stanney et al. (1997) in standard visually-dependent simulators, which was D > N > O, and follows the symptomology found in conditions of visually-induced motion sickness of D > O > N described by Hettinger & Riccio (1992).

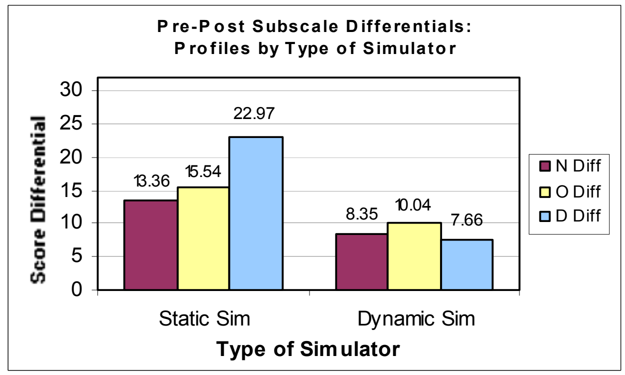

Figure 7. Subscale profile by type of simulator for Pre-Post Differentials.

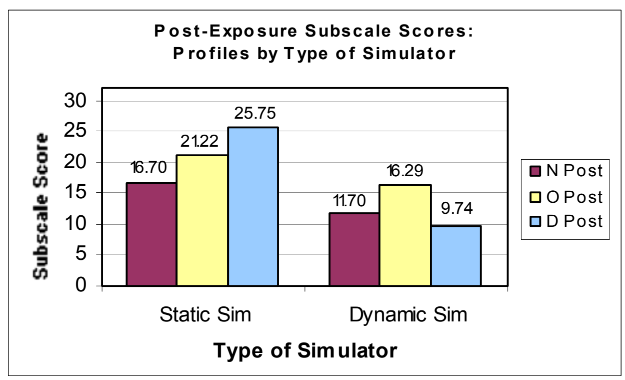

Figure 8. Subscale profile by type of simulator for Post-Exposure Scores.

The subscale profile for *dynamic* simulator participants followed a pattern analogous to that of a motion-based IVE reported by Stanney et al. (1997): O > N > D. Oculomotor discomfort was worse than nausea, followed by disorientation. It serves to reason that subjects who were allowed to physically walk and determine their velocity experienced less disorientation. Note that the dynamic simulator Differentials were low and quite similar to one another, with O=10.04, N=8.35, and D=7.66, while the Post-Exposure oculomotor score was much higher O=16.29. A similar result for oculomotor discomfort was seen for the static simulator, where the computed Differential was 15.54 and the Post-Exposure score was 21.22. These results suggests that any pre-existing oculomotor discomfort was likely exacerbated by exposure to the simulator environments.

DISCUSSION

In this study of locomotion in immersive virtual environments, the influence of type of simulator on SSQ Total Severity scores was substantial. Gender effects found in this investigation have been reported by other researchers (Mourant & Thattacherry, 2000; Kolasinski, et al., 1998). Biocca (1992) notes that the gender effect may be due to underreporting of susceptibility on self-reports by men, but also that other factors, such as hormonal effects and differences in field of view may also be contributors. Other research found that while females had consistently higher simulator sickness scores than did males, the means did not differ significantly at the .05 level (Kolasinski & Gilson, 1998; Rich & Braun, 1996). Kolasinski & Gilson did report that males and females differed on Post-Exposure SSQ Total Severity measures and disorientation subscale measures at the .06 level in their research.

No differences were found in SSQ results when the scores between the distance judgment and movement production activities were compared. Both activities involved generating a mental image of a distance and both tasks required the subject to traverse each distance. While the order of these steps and the measure of performance differed by the task, neither the nature of the simulator exposure nor the complexity of the experience was remarkably different between the DJ and MP task objectives of traversal estimation.

In the range of immersion times experienced in this research, it was demonstrated that increased durations of exposure serve to significantly intensify SS symptomology. In terms of simulator sickness increasing with exposure duration, Stanney and Kennedy (1998) found that with durations near and beyond 30 minutes, the "subjective symptoms may actually lessen with protracted exposure." They attribute this effect to physiological adaptation. In the current research, none of the simulator sessions extended beyond a duration of 23 minutes, with the shortest session lasting only 13 minutes. As such, no adaptation effects were observed.

This study found that a textured visual environment resulted in higher reported simulator sickness than less complex imagery. This effect may be due to simulated texturing being different from what is experienced when traveling through a real-world environment. The quality of texturing in computer graphics is improving rapidly. This effect may diminish and/or disappear with improved systems or may be a function of the complexity of the environment combined with the traversal estimation task requirements.

Allowing subjects to control locomotion in a virtual environment via their own physical activity resulted in approximately a 50% reduction in reported simulator sickness measures. This suggests that the tactile, proprioceptive, kinesthetic, and vestibular feedback associated with the subjects' physical activity played a role in reducing simulator sickness. Consistent with established SS subscale profiles, the symptomology in the static simulator resembled those of visually-dependant IVEs (termed *cybersickness*), while the dynamic simulator pattern of symptoms resembled that of motion-based IVEs (classic simulator sickness).

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