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Effects of Characteristics of Image Quality in an Immersive Environment

Abstract

Image quality issues such as field of view (FOV) and resolution are important for evaluating "presence" and simulator sickness (SS) in virtual environments (VEs). This research examined effects on postural stability of varying FOV, image resolution, and scene content in an immersive visual display. Two different scenes (a photograph of a fountain and a simple radial pattern) at two different resolutions were tested using six FOVs (30, 60, 90, 120, 150, and 180 deg.). Both postural stability, recorded by force plates, and subjective difficulty ratings varied as a function of FOV, scene content, and image resolution. Subjects exhibited more balance disturbance and reported more difficulty in maintaining posture in the wide-FOV, high-resolution, and natural scene conditions.

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1 Introduction

With current and expected technological developments, there is an increasing need to understand the psychological and physiological effects of VEs on humans. Technological shortcomings of VE systems, such as low resolution and limited FOV, limit the use of VE systems and force users to adapt to non-optimal conditions (Stanney & Salvendy, 1998). Consider, for example, VE simulator sickness (SS, or so-called *cybersickness*). Most users experience some level of SS the first time they use a VE system (Regan & Price, 1994). With repeated exposures, users adapt and SS symptoms decrease. Hettinger et al. (1987) suggested that SS may correlate with the ability of a VE to elicit illusory self-motion (vection). Hypothesized contributors to SS also include scene content, FOV, image resolution, motion trajectory, frequency characteristics of scene motion, among others. Postural disturbance has been proposed for evaluating VE systems (Stanney & Salvendy, 1998). Kennedy and Stanney (1996) evaluated postural stability measures for assessing aftereffects from VE exposure. Previous studies (Cobb & Nichols, 1998; Hamilton, Kantor, & Magee 1989) indicate that balance disturbance correlates with simulator sickness. Also, balance disturbance has been suggested as a surrogate measure for SS intensity. Scene content, FOV, image resolution, motion trajectory, and frequency characteristics of scene motion affect vection as well as SS. Vection,

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presence, and SS are related to postural disturbance. In this study, we examine effects of FOV, image resolution, and scene content on postural disturbance.

1.1 Central/Peripheral Vision

Vection has been proposed as a contributor to presence in virtual environments (McGreevy, 1992) and to inducing SS (Kennedy, Hettinger, & Lilienthal, 1990). Because large FOVs stimulate peripheral regions of the retina, they may more effectively produce self-motion perception (Hettinger et al., 1987).

Questions about the region of the retina most responsible for the perception of self-motion has been asked by many researchers. (See Wolpert (1990).) Initial reports indicated that stimulation of peripheral areas of the retina was more effective in eliciting perception of self-motion than was simulation of more-central areas (Dichgans & Brandt, 1978; Held, Dichgans, & Bauer, 1975).

These experiments led scientists to theorize that human vision is mediated by two functionally different systems. Leibowitz and Post (1982) extended the notion of "two modes of processing spatially distributed information" that was proposed by Held (1970) and others. The two-modes model of spatial processing described two different kinds of visual functions associated with different parts of the brain. These are the focal mode and the ambient mode. The former was thought to be responsible for object recognition and identification and concerned with the "what" question, and the later was thought to be responsible for spatial orientation, locomotion, posture, and concerned with the "where" question.

Several studies examined this theory. Brandt, Dichgans, and Koenig (1973) found that, when the central retina was stimulated, self-motion was not experienced, but strong self-rotation was elicited when the peripheral retina was exposed to optical flow. Hulk and Rempt (1983) using sine-wave gratings of various widths, found that self-motion was most frequently reported at FOV eccentricities of 50 deg. and 60 deg., with the slower angular velocities of 10–15 deg./sec. proving most effective. Howard and Heckmann (1989) reported that, when stimuli were presented in the peripheral visual field, the self-motion experienced by subjects was stronger than when the stimuli were presented in the central visual field. However, vection was reduced when the central stimuli moved opposite to the direction of the peripheral stimuli. Howard, Ohmi, Simpson, and Landolt (1987) reported that strong vection could be evoked by a centrally located moving pattern if that pattern was perceived as being more distant than a stationary surround. Vection appears to be strongly related to the perceptual distinction between foreground and background.

Warren and Kurtz (1992) reviewed several experiments that contradicted the peripheral dominance hypothesis of Brandt et al. (1973): that peripheral vision is specialized for self-motion perception. Based on studies of perceived heading accuracy, Warren and Kurtz found that the periphery is less sensitive to radial optical flow than the central region. Even FOVs as small as 10–25 deg. evoked self-motion perception. Stoffregen (1985) reported that postural adjustments were evoked by either radial or parallel (lamellar) optical flow in the central visual field but only by lamellar flow in the periphery. Anderson and Braunstein (1985) found that, with a display subtending angle as small as 7.5 deg., subjects still reported vection and motion sickness. They suggested that representation of motion in depth might be the critical element in perceiving self-motion.

1.2 FOV/SS/Presence/Spatial Awareness

Several investigators have examined the effects on SS and performance of image-quality variables such as FOV and resolution. Stanney and Salvendy (1998) proposed that FOV and display resolution may affect the usability of a display system and may correlate with motion sickness. Users usually report higher incidence of SS with a wide-FOV display than with a narrow one (Kennedy, Lilienthal, Berbaum, Berbaum, & McCauley, 1989). A wide-FOV display can maximize immersion of the user in the virtual environment. DiZio and Lackner (1997) evaluated 21 subjects in two different FOV conditions. Subjects reported more motion sickness symptoms during 15 min. exposures when using a head-

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mounted display (HMD) with a wide FOV (138 deg. horizontal by 110 deg. vertical) than did subjects who were exposed to a FOV half as large. Narrow FOVs may degrade the sense of presence (Prothero & Hoffman, 1995; Hettinger et al., 1987). Users' experience of SS varied with VE systems characteristics. There is no generally accepted conclusion regarding the relationship between SS and presence. Some studies showed that they are positively correlated; other studies reported a negative correlation. (See Stanney and Salvendy (1998).) Stanney and Salvendy suggested that both SS and presence may correlate with intervening variables such as vection.

FOV may also influence spatial awareness in VEs. Witmer, Bailey, and Knerr (1994) reported that, when subjects moved through a VE, limited FOV could cause frequent collisions with walls and doorways. Subjects apparently failed to detect VE features such as intersections between the walls and floor. Kline and Witmer (1996) found that distance estimates were also affected by FOV. They tested twelve different viewing distances in a VE (1 to 12 ft.). Subjects overestimated distances when presented with a narrow FOV (60 by 38.5 deg.) and underestimated the same distances with a wide FOV (140 by 90 deg.). Limited FOV interfered with development of spatial knowledge and increased navigational difficulties (Alfano & Michel, 1990). McCreary and Williges (1998) reported that, when using an HMD, larger FOVs resulted in greater route and configuration knowledge, although landmark knowledge was not significantly changed. Kenyon and Kneller (1993) examined a visual nulling task at five different FOVs (10, 20, 40, 80, and 120 deg.). They found that subjects' minimum RMS error occurred at 80 deg., not 120 deg. Also, subjects reported greater task difficulty at the 120 deg. FOV than at 80 deg. They suggested that subjects experienced stronger vection at the 120 deg. FOV, making the nulling task more difficult.

1.3 Image Resolution

Pausch, Crea, and Conway (1992) suggested that display FOV is only one of several factors that may contribute to SS. Higher picture resolution and quality may allow more information to be present in particular display areas. Higher resolution permits increased scene information and "realism." Welch, Blackmon, Liu, Mellers, and Stark (1996) found that pictorial realism correlated with perceived sense of presence. However, it is difficult to evaluate effects of resolution and realism because of possible interactions with other display characteristics such as FOV.

Ziefle (1998) investigated effects of three different resolutions, using a cathode-ray tube (CRT) display, on eye movements during a visual search task. Reaction times and fixation durations were increased in the low-resolution condition (62 dots per inch (dpi) 720×540 pixels) as compared with the high-resolution condition (89 dpi, 1024×768 pixels) by 19% and 9.6%, respectively. Gould, Alfaro, Finn, Haupt, and Minuto (1987) found that the higher the resolution of the display, the better the reading performance. Kline and Witmer (1996) studied the effects of three texture resolutions (512×512 pixels, 16×16 pixels, and no texture) and two texture types (rich and emergent, and poor and nonemergent) on distance estimates. They found that fine texture resolution improved the accuracy of estimates for distances under 6 ft. when using a narrow FOV. They suggested that higher texture resolution might improve depth perception and distance estimation in a narrow-FOV VE system. However, Watson, Walker, Hodges, and Worden (1997) found that degrading visual resolution in the periphery did not significantly reduce visual search performance.

1.4 Problem

Previous studies suggest that FOV and resolution affect task performance in VEs. Also, the experience of self-motion depends in part on motion cues in the peripheral region of the retina. Wide-FOV displays can elicit greater immersion in the VE and may enhance the experience of presence. Bullinger, Bauer, and Braun (1997) recommended using a 120 deg. horizontal by 60 deg. vertical FOV and 9000×3600 pixel resolution for VE systems. On the other hand, stronger vection, which is one of the factors that may contribute to SS, is also more likely with such a display. Both FOV and res-

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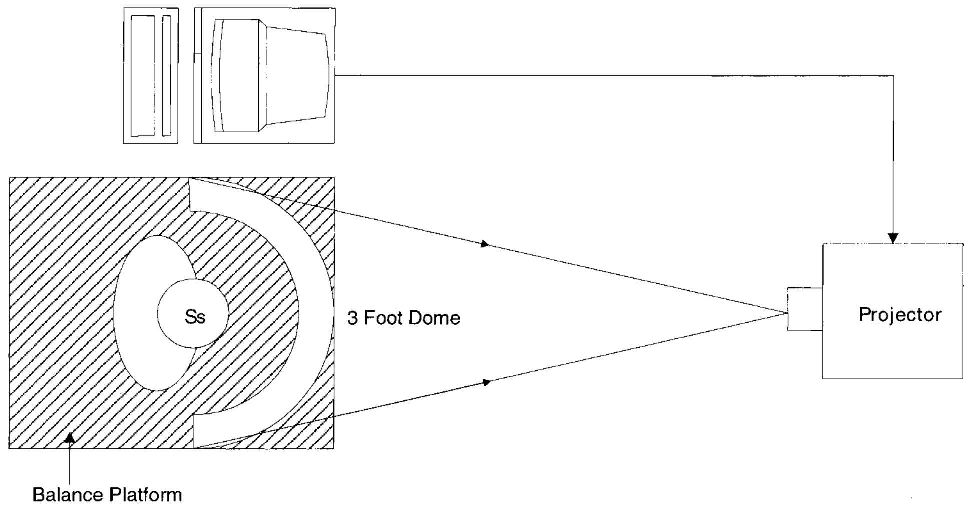

Figure 1. *Equipment layout.*

olution are critical issues for VE research. Moreover, interactions between FOV and resolution need to be evaluated.

As noted, previous research indicates that postural stability is related to self-motion perception, presence, and SS. This study used postural stability measures to investigate the effects of different FOVs, scene resolutions, and scene contents.

2 Experiment

2.1 Subjects

Ten subjects (seven women and three men), ages twenty to thirty, 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 vision. Subjects were paid $10/hour, and the protocol was approved by the University of Washington Human Subjects Review Committee.

2.2 Apparatus

The experimental setting is shown in figure 1. Visual scene motion was generated by computer software. The scene update rate was about sixty frames per second. Two computer-generated scenes (fountain scene (the University of Washington Fountain) and simple scene (the radial pattern)) with two resolutions (600 × 600 dpi and 256 × 256 dpi) were used. (See figure 2.) The back-projected images from a Kodak DP1100 projector (1024 × 768 pixel resolution) were presented on a 3 ft. dome which has a nominal 180 × 180 deg. FOV. Subjects stood on a Chattecx balance platform that automatically calculated dispersion around the center of balance based on signals (100 Hz sampling rate) generated by force plates under their feet.

2.3 Procedure

Frontal visual scene roll oscillation was presented at a low frequency (0.05 Hz). (See Parker, Duh, Philips, and Furness (2001).) Peak scene angular velocity was constant at approximately 70 deg./sec. Three different scenes (600 dpi fountain scene, 600 dpi simple scene, and 256 dpi fountain scene) were presented at six different FOVs (+/− 15, 30, 45, 60, 75, and 90 deg. from the center of the visual field). Data were collected with the subjects in a sharpened Rhomberg stance (Hamilton et al., 1989). They stood on the balance platform, one foot in front of the other and with their arms crossed

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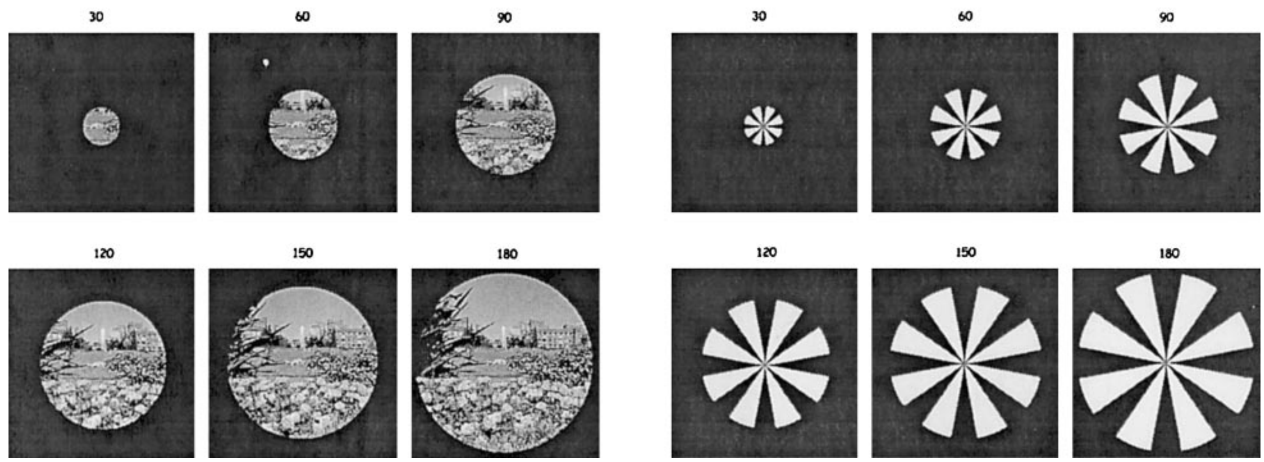

Figure 2. *Stimuli: high-resolution (600 × 600 dpi) fountain scene and simple radial pattern scene (600 × 600 dpi).*

behind their backs, as described by Parker et al. (2001). Four trials (replicates) were collected in each stimulus condition, and 10 sec. periods of baseline data while viewing a static scene were collected before and after the visual stimulus trials. For the experimental conditions, the subjects looked at the moving scene for 10 sec. while holding the support bars, assumed the Rhomberg position, and attempted to stand steady during the 10 sec. data collection. The subject's eyes were closed except during the visual stimulus trials. The order of FOV conditions was partially counterbalanced across all subjects. To avoid fatigue and learning effects, the experimental conditions were presented in two sessions with a three-day interval between sessions. The subjects' rating of difficulty (difficulty in maintaining the Rhomberg stance, 1–10 scale, with 1 the easiest and 10 the hardest) and the dispersion of center of balance were collected for each trial. (Dispersion is a measure of variability with respect to the center of balance in the two-dimensional—fore-aft and side-to-side—plane of the balance platform.)

3 Results

Because of large inter- and intrasubject variability, subjective difficulty ratings and balance dispersion scores were standardized: each visual trial score was divided by the average baseline performance for that subject. Results from this study are summarized in figure 3. Means for the dependent variables were calculated using repeated-measures ANOVAs. For the dispersion data, there was a statistically significant main effect of scene ($F(2, 18) = 61.978$, $p < .01$); the main effect of FOV was also significant ($F(5, 45) = 50.621$, $p < .01$) as was the interaction between scene and FOV ($F(10, 90) = 5.949$, $p < .01$). Subjects responded differently to the different scenes, and dispersion increased with increasing FOV for all three visual conditions. Larger differences between scenes were obtained with the larger FOVs. For the rating data, the main effects of scene, FOV, and interaction were similar to those obtained using the dispersion data ($F(2, 18) = 35.597$, $p < .01$; $F(5, 45) = 69.941$, $p < .01$; $F(10, 90) = 2.058$, $p < .05$, respectively). Selected post hoc analyses of the dispersion data indicated differences between FOVs for all intervals (30–60, 60–90, 90–120, 120–150, and 150–180 deg.). The largest difference was for 150–180 deg. For the rating data, there were differences for the 30–60, 60–90, 90–120, and 120–150 deg. intervals. The largest difference was for 90–120 deg.

To examine further the effect of resolution, we compared the high-resolution and low-resolution fountain scenes across the FOV conditions. For the dispersion

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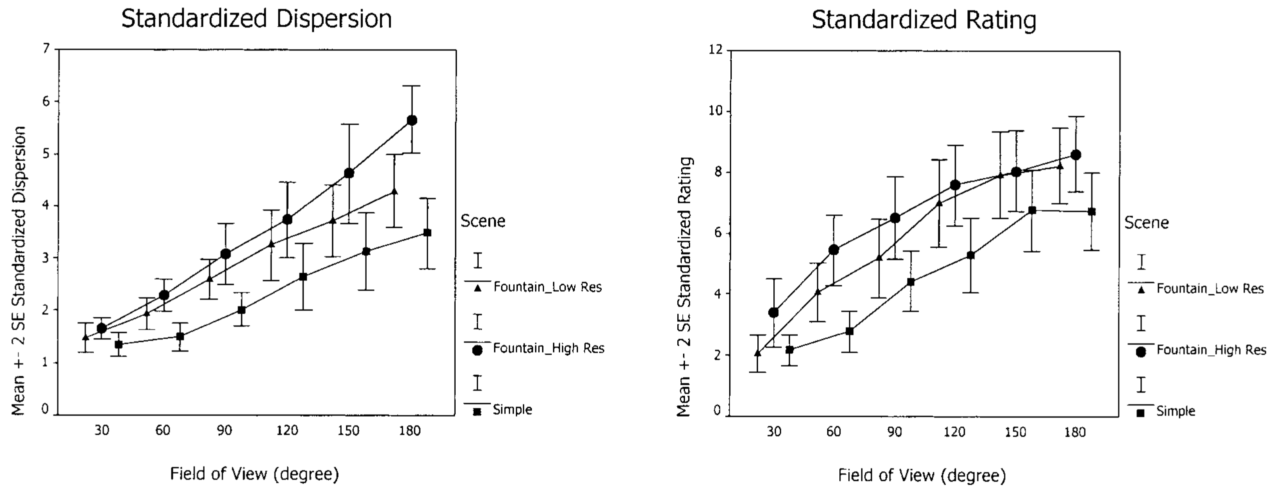

Figure 3. *Means and standard errors standardized ratings and dispersions as a function of field of view for simple and fountain scenes. (Note: To preserve readability, the error bars and mean data points for the FOV conditions are staggered.)*

data, the main effect of resolution was significant ($F(1, 9) = 60.010$, $p < .01$) as was the interaction between resolution and FOV ($F(5, 45) = 6.116$, $p < .01$). Subjects exhibited increased dispersion with increasing FOV and resolution. With increasing FOV, the disturbance differences between resolutions increased. For the rating data, the main effects of resolution and FOV were also significant ($F(1, 9) = 18.408$, $p < .01$; $F(5, 45) = 65.530$, $p < .01$, respectively). However, the interaction between resolution and FOV was not significant for the rating data.

To examine further the effect of scene content, we compared the high-resolution fountain and high-resolution simple radial pattern scene across FOV conditions. For the dispersion data, the main effect of scene content was significant ($F(1, 9) = 72.065$, $p < .01$), the main effect of FOV was significant ($F(5, 45) = 48.695$, $p < .01$), and the interaction between resolution and FOV was significant ($F(5, 45) = 10.000$, $p < .01$). Subjects exhibited increased dispersion with increasing FOV and more-complex scene content. With increasing FOV, the disturbance differences between different scenes increased as well. For rating data, the main effects of scene and FOV were also significant ($F(1, 9) = 56.911$, $p < .01$; $F(5, 45) = 56.258$, $p < .01$, respectively). However, the interaction between scene content and FOV for the rating data was not significant.

4 Discussion

All the data showed the same trend: with increasing FOV, subjects exhibited more dispersion and reported more difficulty keeping their balance. For the standardized dispersion data, failure to observe "saturation" at the extreme FOVs was surprising. Subjects' standardized dispersion continued to increase up to the largest FOV across all three visual conditions. With increasing FOV, subjects received more information from their peripheral visual field, and this peripheral stimulation apparently caused greater postural disturbance. These findings support previous assertions that wide FOVs cause greater self-motion perception and postural disturbance. The results also suggest that people in wide-FOV, high-resolution displays might report more SS and presence.

In contrast to the dispersion results, there is a plateau in the difficulty rating data. The plateau occurred between 120 deg. and 150 deg. FOVs across the three visual conditions. Possible explanations for this include

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the following. First, the subjects' perceptual scale for difficulty rating may have "saturated." During postexperiment debriefings, several subjects reported that they could not tell the difference between 150 deg. and 180 deg. FOV conditions and that it was hard for them to maintain balance in both conditions. Second, the rating data may reveal a "ceiling effect." Subjects frequently fell in both the 150 deg. and 180 deg. FOV conditions. The highest rating scale value (10) was automatically assigned when subjects broke stance or fell.

Interestingly, small FOVs can evoke substantial postural disturbance. Our results showed that even the 30 deg. FOV evoked postural disturbance 1.5 times as large as the baseline condition for standardized dispersion and two times more than baseline for standardized rating. The data are consistent with Howard and Heckmann's (1989) results for vection but in opposition to the Brandt et al. (1973) peripheral dominance hypothesis. Our results are consistent with the functional sensitivity hypothesis proposed by Warren and Kurtz (1992). In contrast to Brandt's peripheral dominance hypothesis, they proposed that central and peripheral vision are sensitive to different information. Apparently, self-motion perception is evoked by different classes of optical information. Central retinal cells extract radial, rotary, and lamellar flow information, whereas peripheral cells respond to lamellar flow pattern (Stoffregen, 1985).

Duh, Parker, and Furness (2001) used an "independent visual background" (IVB) in the peripheral or central visual field to reduce scene motion-induced balance disturbance. They were surprised to find that an IVB located in the visual periphery was less effective than one located in the central visual field. This finding may be explained by Stoffregen's results and functional sensitivity hypothesis. It is possible that central and peripheral cells differ in their ability to parse moving scene and static information. Further experiments to explore the differences in central and peripheral processing are needed.

Scene content and resolution also appear to be important variables. Subjects exhibited greater postural disturbance and reported more difficulty in maintaining upright posture with the fountain scene than with the simple scene when both were presented at high resolution. The fountain scene provides more 2-D (monocular) depth cues, more up-down polarity cues, and more-meaningful information than the simple scene. Also, there was a significant interaction between FOV and scene content. Subjects exhibited small differences in dispersion with narrow FOVs but large differences with wide FOVs. Larger FOVs may provide more depth cues.

Subjects also exhibited greater postural disturbance and reported more difficulty in maintaining upright posture with the high-resolution fountain scene than with the low-resolution fountain scene. Dispersion differences between high- and low-resolution scenes in the wide-FOV condition were larger than in the narrow-FOV condition. Apparently, the higher spatial frequencies in the high-resolution scene conveyed a greater sense of realism than did the low-resolution fountain scene.

This study demonstrated relationships between postural disturbance and both FOV and scene resolution. As noted, previous studies indicate that postural disturbance correlates with presence and SS. Therefore, our results in conjunction with previous research suggest that FOV and scene resolution are related to presence and SS.

In summary, the results from this experiment indicated that postural stability varied as a function of display FOV, resolution, and scene content. Subjects exhibited more balance disturbance with increasing FOVs, higher resolutions, and more-complex scene contents. This implies that, when we present scenes with different contents, different levels of interactivity, and different resolutions in immersive environments, different FOVs may be required to minimize postural disturbance. Further, our results suggest that, to achieve a minimum level of presence, the characteristics of image quality should be carefully addressed. Future research will focus on relationships among independent variables including FOV, image resolution, scene content, and interactive control using presence and performance as dependent variables.

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