Height Effects in Real and Virtual Environments

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The study compared human perceptions of height, danger, and anxiety, as well as skin conductance and heart rate responses and postural instability effects, in real and virtual height environments. The 24 participants (12 men, 12 women), whose average age was 23.6 years, performed "lean-over-the-railing" and standing tasks on real and comparable virtual balconies, using a surround-screen virtual reality (SSVR) system. The results indicate that the virtual display of elevation provided realistic perceptual experience and induced some physiological responses and postural instability effects comparable to those found in a real environment. It appears that a simulation of elevated work environment in a SSVR system, although with reduced visual fidelity, is a valid tool for safety research. Potential applications of this study include the design of virtual environments that will help in safe evaluation of human performance at elevation, identification of risk factors leading to fall incidents, and assessment of new fall prevention strategies.

INTRODUCTION

Virtual reality (VR) technology has significant potential to create advances in a number of fields, such as medicine, engineering, design, training, and entertainment; however, systematic human factors research is needed to realize this potential (Stanney, Mourant, & Kennedy, 1998). More specifically, there is a broad need for direct comparisons of human behavior in virtual and real environments (Stoffregen, Bardy, Smart, & Pagulayan, 2003).

VR technology is a promising tool for occupational safety research. It may allow researchers to safely study humans in simulated dangerous work environments. For example, very few empirical studies have addressed fall hazards on roofs and scaffolds because of the associated risk of study-related injury, but a virtual model of height will allow such research without endangering human participants. Successful applications of this model, however, require comprehensive evaluation of VR model effectiveness.

Humans detect and recognize elevation and exposure to elevation exclusively by available visual information. Elevation in the environment is perceived by the observer as a vertical distance from the surface of support to a lower surface – that is, height perception is a special case of depth perception (Gibson & Walk, 1960). Exposure to elevation may induce a psychological effect of fear of falling, leading to physiological and behavioral protective responses and a degradation in human balance control.

Human responses to height have been studied in infants and young children, using the classical "visual cliff" experimental paradigm (Gibson & Walk, 1960). Acrophobia research has suggested that the level of experienced anxiety in a specific height exposure depends on the perception of danger, which is a function of the perceived risk of falling and the severity of the expected injury (Menzies & Clarke, 1995). The risk of a fall from elevation might be mediated by a number of factors, including posture and task, distance to the elevated edge, stability of the support surface, and availability of fall-protective devices (Hsiao & Simeonov, 2001). The perceived severity of injury from a fall is affected mainly by the fall height, body mass, expected body orientation at impact, and type of the surface to be impacted (Warner & Demling, 1986). The psychological

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effect of fear of falling may trigger corresponding physiological responses, including an increase in heart rate (Emmelkamp & Felten, 1985). Personal danger perceptions are mediated by individual experiences and can be significantly reduced by habituation (Zimolong, 1985).

Human responses to height in virtual environments have been evaluated in research on the treatment of acrophobia (Hodges et al., 1995) and research on "presence" in immersive virtual environments (Meehan, Razzaque, Whitton, & Brooks, 2003; Regenbrecht, Schubert, & Friedman, 1998). These studies recorded a range of fearful reactions and physiological responses in both acrophobic and normal, healthy participants. However, it is still unclear whether the fearful responses from exposure to real and virtual heights are comparable. Recently, Emmelkamp et al. (2002) found that virtual height exposure is at least as effective as real height exposure for treatment of acrophobia. Rothbaum, Hodges, Anderson, Price, and Smith (2002) reported similar outcomes in treatment of fear of flying. These research findings suggest that exposures to real and virtual height have comparable therapeutic effects on acrophobic participants. However, height effects in real and virtual environments have not been comparatively evaluated in healthy, nonacrophobic participants.

Previous research has shown that exposure to height can affect a person's balance because of degraded visual stabilization (Bles, Kapteyn, Brandt, & Arnold, 1980). The distant scenes at elevation are not effective as visual references, and body sway increases (Lee & Lishman, 1975; Paulus, Straube, & Brandt, 1984). In addition, the destabilizing effect of height is significantly amplified under more challenging support conditions – that is, on deformable (Simeonov & Hsiao, 2001) or sloped surfaces (Simeonov, Hsiao, Dotson, & Ammons, 2003). However, it is not known if these effects can be adequately simulated in virtual environments of elevation.

Finally, prolonged exposure to VR can cause cybersickness (Kennedy & Lilienthal, 1994), which has been associated with postural instability (Riccio & Stoffregen, 1991). However, most of the previous research evaluated postural stability only before and after VR exposure (Cobb, 1999). The destabilizing effects of real and virtual environments of elevation have not been comparatively evaluated.

The objective of this study was to evaluate the effectiveness of a height simulation by a surround-screen virtual reality (SSVR) system as a tool for modeling elevated workplaces in occupational safety and fall-prevention research. Based on previous experimental studies (Bles et al., 1980; Emmelkamp et al., 2002; Meehan et al., 2003) and theories (Riccio & Stoffregen, 1991), our hypothesis was that virtual and real height can induce similar perceptions, physiological responses, and postural instability effects.

METHOD

Participants

Twenty-four volunteers (12 men and 12 women) with average age of 23.6 years (range 19–37 years) participated in the study. The participants' average height was 171.7 cm (*SD* = 8.8 cm), and their average weight was 69.6 kg (*SD* = 16.3 kg). Participants were recruited from the general population in the Morgantown, West Virginia, area. The requirements for study participation were normal or corrected vision, not acrophobic, no balance problems, no medication use, no alcohol consumption in the last 24 hr, and age of 18 years or older. The participants' average acrophobia score (Cohen, 1977) was 12 (*SD* = 7.83), which was comparable to the scores of nonacrophobic groups in other studies (Menzies & Clarke, 1995). We estimated that the number of participants we recruited would allow detection of effect sizes approximately equal to one standard deviation with statistical power higher than .8, at significance level .05. The study protocol was approved by the Institute Review Board of the National Institute for Occupational Safety and Health.

Independent Variables

The study used a balanced repeated measures design that involved an exposure task with the independent variables of visual environment and height, and a standing balance task with the independent variables of visual environment, height, close visual target, and surface firmness.

Visual environment. This variable had two levels: real environment (RE) and virtual environment (VE). The RE was the interior of a "high-bay" laboratory. The VE was created in the VR system, in which the existing visual structures of the real high-bay lab were simulated with reasonable accuracy (Figures 1a and 1b). The VE differed slightly from the RE in some aspects, including visual detail, image resolution, color, contrast, and dynamic response to movement. The participants wore stereo shutter glasses during all tests, in the RE and the VE, to maintain a comparable visual field.

Height. The standing surface height had three levels: 0, 3, and 9 m. The tests in the RE were conducted on two balconies, which were equipped with protective railings, and at the ground level in the lab. A similar protective railing was constructed at the ground level of the lab to provide comparable environmental conditions for the baseline exposure task. The experimental conditions for the standing balance tasks in RE have been previously described (Simeonov et al., 2003). The participants were protected from falling while standing behind the railing, which minimized the height-related psychophysiological effects on their balance (Adkin, Frank, Carpenter, & Peysar, 2000). The tests in the VE were conducted with the SSVR system. The participants stood on the floor (the lower screen) of the system while the system visually simulated

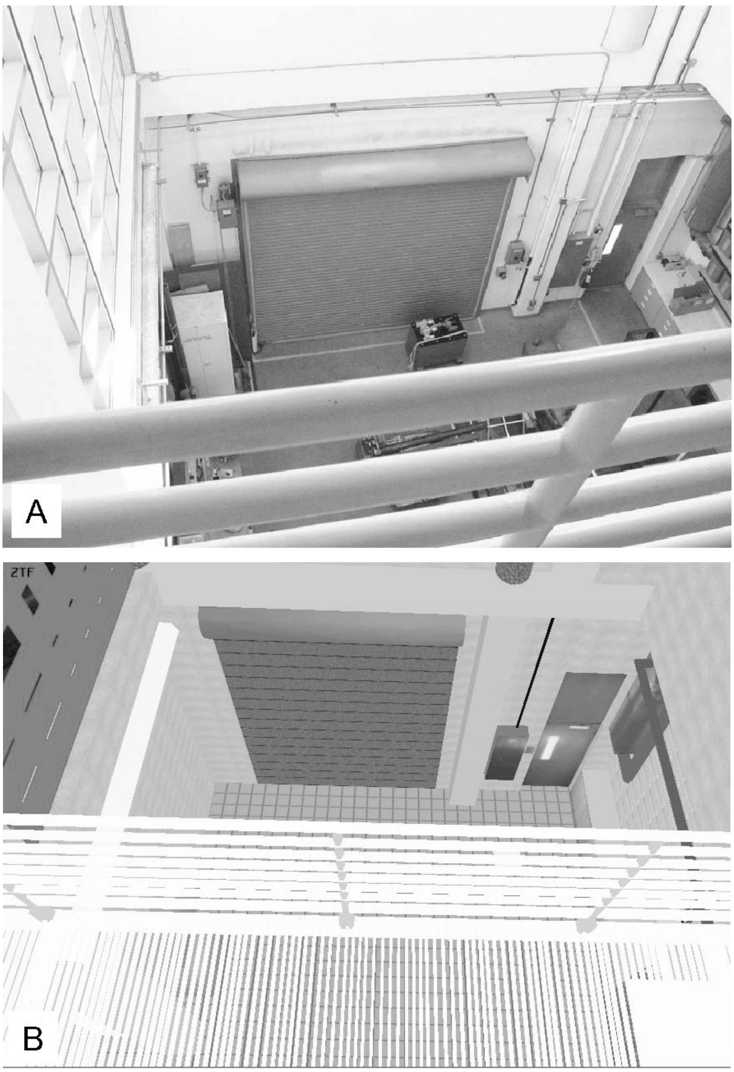

Figure 1. View over the railing at the 9-m-high balcony: (a) real environment; (b) virtual environment.

the different height levels of the high-bay laboratory environment.

Close visual target. This variable was used to compare visual stabilization effects at height in RE and VE. Looking at a close visual target is associated with reduced postural sway (Paulus et al., 1984; Stoffregen, Pagulayan, Bardy, & Hettinger, 2000). The variable had two levels, with the target present or not present. The target was a 4 × 4 cm vertical bar at a distance of 50 cm in front of the participant. The participant was instructed to look at the bar when it was present in the visual environment or to look at the visual background in the alternative condition.

Surface firmness. Two levels of surface firmness were evaluated: a firm, stable work surface and a deformable support simulating an unstable work surface. Participants were standing directly on the force platform or on a foam pad, with thickness 10 cm and density 0.080 g/cm^3, placed on the force platform.

Dependent Variables

Perceptions. Participants' anxiety and danger perceptions were obtained after each exposure task using a method adopted from Menzies and Clarke (1995). The participants rated their perceived anxiety (PA) on a scale ranging from 0 (*no anxiety*) to 10 (*worst anxiety*); perceived risk of falling (PR) on a scale from 0 (*not possible*) to 10 (*certain*); and perceived potential injury (PI) on a scale ranging from 0 (*no injury*) to 10 (*death*). In addition, the participants gave a verbal report of the perceived height (PH), which was normalized to the real or simulated height for further analyses.

Physiological measures. Baseline physiological levels were assessed before each exposure task to control for nonspecific environment and time-related drifts. The baseline levels were calculated from the data recorded in the last 3 min of a 5-min seated rest period before each task to reduce the effects of fatigue. Mean task levels were calculated from data recorded during a period of 45 s, which included the 15-s phase of approach and exposure (i.e., bending and looking over the railing) and a 30-s period after the exposure to account for the response latency. The heart rate response (HR) and skin conductance response (SC) were calculated as normalized differences of the mean task and mean baseline values.

Standing balance parameters. Three dependent variables derived from the center of pressure movement were used to quantitatively describe sway and postural stability: root mean square of medial-lateral (ML) and anterior-posterior (AP) sway and mean sway velocity (V). ML and AP are suitable measures for average body sway (Bles et al., 1980), and V is an appropriate measure of postural stability (Le Clair & Riach, 1996).

Equipment

Physiological measurement system. Physiological data were collected using the ambulatory data recorder (Biolog 3992, UFI, Morro Bay, CA). The HR was recorded via three electrodes attached to the chest and the SC with two silver/silver chloride electrodes placed on the ring and index fingers of the left hand. The heart rate data were scanned for outliers and edited using the method described by Porges and Byrne (1992).

Kinetic measurement system. The equipment for the center-of-pressure measurements was a portable force platform (Accusway, Advanced Mechanical Technologies, Inc., Watertown, MA). Data were collected with a portable personal computer at a 50-Hz frequency.

Virtual reality system. The projection-based SSVR system had three 3.6 × 3.0 m walls and a 3.6 × 3.6 m floor. An SGI Onyx computer system with two Infinite Reality graphics pipelines, each split into two channels, controlled the projected images at a resolution of 1024 × 768 and a 96-Hz stereo signal for a 48-Hz effective scene refresh rate. The liquid crystal shutter glasses (Crystal Eyes-2, StereoGraphics Inc., San Rafael, CA) limited the participant's field of view to approximately 100° in the horizontal and 50° in the vertical direction. The average time delay of the system was approximately 55 ms, measured by the method of Adelstein, Johnston, and Ellis (1996). The VE was drawn to scale from blueprints of the RE. Digital photographs of the RE were used to create texture maps and add visual detail.

Procedure

The participants were briefed on the study objectives, methods, procedures, and potential risks. The participants completed the acrophobia questionnaire and changed into safety shoes (men's Model 292 women's Model 449, Iron Age Corp., Pittsburgh, PA). The participants were then fitted with electrodes and taken to the real or the virtual lab to start the tests.

The order of environments and the height levels within each environment were counterbalanced. At each height level the participants first performed one exposure task followed by four standing balance tasks. Before the exposure task the participants sat quietly in a chair for 5 min to get their physiological parameters within resting ranges. After the exposure task the participants rated their perceived anxiety, risk of falling, and potential injury and gave an estimate of the height distance. The balance tasks involved quiet standing with feet at a 30° angle and heels together for 30 s. Each balance task was repeated three times and was followed by a 3-min seated rest period to reduce the possibility of fatigue. Baseline balance tasks in which the participants stood on firm or deformable support and had their eyes closed were also included.

During the experimental procedures, special care was taken to prevent the participants from being exposed to the height environment while moving from one height level to another or during the resting periods. In the VE the participants had approximately 30 s of orientation time before starting the tests. In addition, before the start and after the completion of the test session in the VR lab, two balance performance tests (National Highway Traffic Safety Administration, 2000) were given to the participants to ensure that the VE exposure had produced no adverse effects. The participants completed the experiment in approximately 3 hr and were compensated for their time.

RESULTS

Perceptions

A 2 × 2 (Environment × Height) analysis of variance (ANOVA) was performed on each of the reported perceptions, except for ground level in the height variable because all the responses at this level were zero. The analysis indicated similarly increased anxiety from height exposure in VE and RE. The main effect of visual environment, $F(1, 23) = 2.24$, $p = .15$, and the interaction of visual environment and height $F(1, 23) = 1.84$, $p = .17$, did not reach statistical significance. The visual environment equivalence test, using a 95% confidence interval (CI) and a ±10% equivalence range (Jones, Jarvis, Lewis, & Ebbutt, 1996), was inconclusive. There was a significant positive main effect of height $F(1, 23) = 11.09$ $p < .01$, which accounted for 7.9% of the total variance.

The reported risk of falling was very low, and the PR analysis did not show significant effects. However, participants perceived a more severe potential injury from a fall in RE than in VE, $F(1, 23) = 29.98$, $p < .001$. The negative main effect of visual environment accounted for 6.2% of the total variance. There was also a positive main effect of height $F(1, 23) = 169.00$, $p < .001$, which accounted for 56.1% of the total variance. As expected, participants strongly associated increased height with increased severity of injury.

The HP analysis indicated significant negative effect of visual environment $F(1, 23) = 18.79$, $p < .001$, which accounted for 18.4% of the total variance. The participants overestimated height in the RE, whereas in the VE their estimates were nearly identical to the simulated height distances.

Physiological Responses

A 2 × 3 (Environment × Height) ANOVA was performed for each of the physiological responses. The skin conductance analysis indicated comparable effects from height exposure in VE and RE. Although the SC responses in RE were consistently higher than in VE (14.06% vs. 10.98% at 3 m, and 14.36% vs. 10.88% at 9 m), the visual environment effect did not reach statistical significance $F(1, 23) = 3.63$, $p = .07$. The visual environment equivalence test (95% CI, ±10% range) was inconclusive. There was a significant positive main effect of height $F(2, 46) = 9.97$, $p < .001$, which accounted for 7.9% of the total variance.

Heart rate analyses demonstrated different responses to height in RE and VE (Figure 2). The significant two-way interaction of visual environment and height, $F(2, 46) = 14.45$, $p < .001$, revealed that real height increased HR similarly at 3 and 9 m, whereas virtual height did not

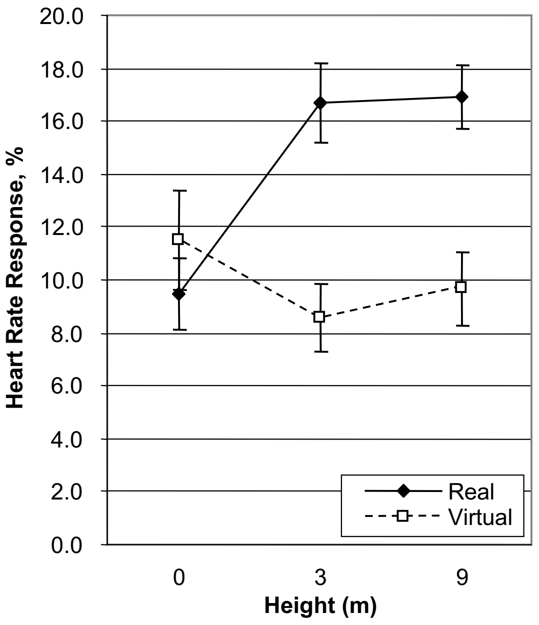

Figure 2. Visual environment and height interaction on heart rate response.

affect HR. The negative effect of visual environment accounted for up to 16.9% of the total variance.

Standing Balance Parameters

A 2 × 3 × 2 × 2 (Environment × Height × Visual Target × Surface) ANOVA was performed on the standing balance parameters. ML sway analysis indicated significant main effects and interactions for all independent variables, including a four-way interaction, $F(2, 46) = 5.29$, $p < .01$. The positive effect of visual environment varied within experimental conditions and accounted for up to 10.8% of the total variance. Participants' ML sway at real and virtual height was not significantly different ($p > .05$) on the firm surface and was statistically equivalent (95% CI, ±10% range) on the deformable surface (Figure 3a). ML sway in the VE was bigger than in the RE at the ground level and at height with close visual target, and the differences were larger on the deformable surface (Figure 3b).

AP sway analysis indicated significant main effects and interactions of visual environment, height, and surface, including their three-way interaction $F(2, 46) = 6.04$, $p < .01$. The positive effect of visual environment varied within experimental conditions and accounted for up to 3.9% of the total variance. Participants' AP sway at real and virtual height was not significantly different ($p > .05$) on the firm surface and was statistically equivalent (95% CI, ±10% range) on the deformable surface. AP sway in VE was bigger than in RE at the ground level only on the deformable surface (Figure 4).

Sway velocity analysis showed significant main effects and interactions for all variables, including three-way interactions for environment, height, and surface $F(2, 46) = 13.15$, $p < .001$, and environment, target, and surface, $F(1, 23) = 30.49$, $p < .001$. The positive effect of visual environment accounted for up to 15.4% of the total variance. Participants' sway velocity was larger in VE than in RE only on deformable support, and the difference between VE and RE was smaller at height and larger at the ground level (Figure 5a). The difference between the two environments was smaller when participants were looking at a distant background and larger when they were looking at a close visual target (Figure 5b).

DISCUSSION

The SSVR system appeared to be an effective elevated-workplace simulator, providing slightly degraded but realistic height-related perceptions in the VE as compared with the RE. The similar levels of mild anxiety and perceived risk of falling in the RE and VE corresponded to the minimal risk present in the RE and simulated in the VE. The participants appropriately associated the increased height with an increased potential for more severe injuries both in the RE and in the VE. Furthermore, the reduced severity of injury perceptions in the VE corresponded well to the degraded height perceptions.

The height perception results in this study demonstrate that the VE provided effective simulation of the RE: The perceived height in the VE corresponded to the simulated height. However, because the participants considerably overestimated the height distances in the RE, height in the VE was underestimated in comparison. These results are consistent with previous studies reporting overestimation of height in RE (Sinai, Ooi, & He, 1998) and underestimation of distance in VE as compared with RE (Witmer & Sadovsky, 1998).

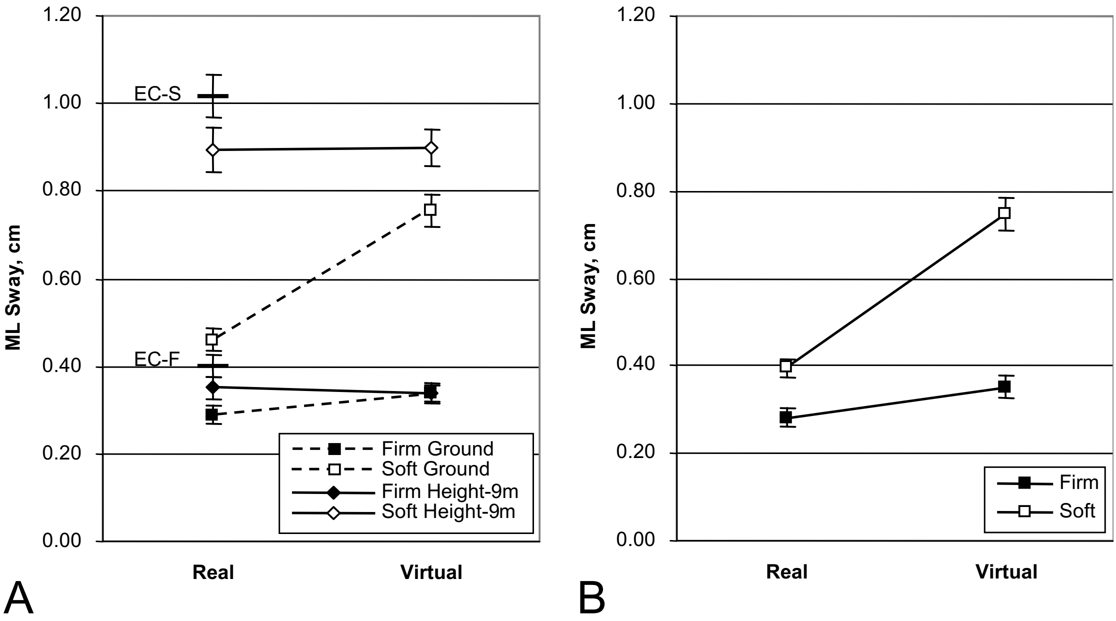

Figure 3. Interaction of visual environment, height, close visual target, and surface firmness on ML sway. (a) Looking at the visual background, distant at height and close at the ground. (b) Looking at a close visual target. EC-S = eyes closed, soft support; EC-F = eyes closed, firm support.

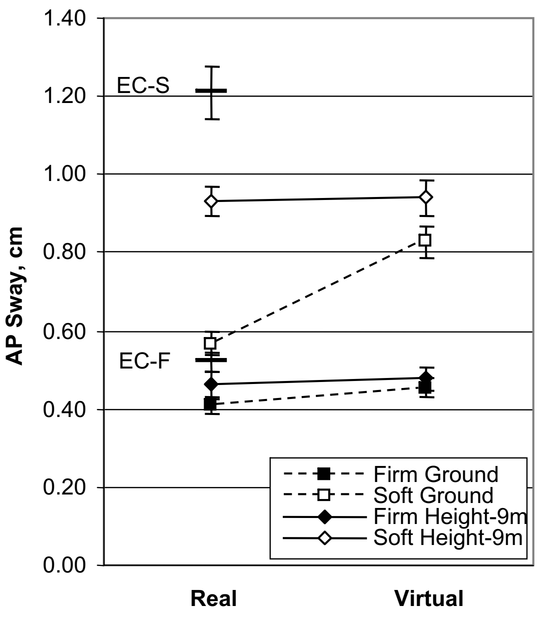

Figure 4. Interaction of visual environment, height, and surface firmness on AP sway. EC-S = eyes closed, soft support; EC-F = eyes closed, firm support.

The comparable skin conductance responses from height exposure in VE and RE further demonstrate the validity of using the virtual model in the SSVR system to induce realistic height-related arousal. The heart rate responses, however, may reflect a less fearful experience from height exposure in the VE as compared with the RE. The different physiological response patterns in VE and RE may reflect different emotional states (Levenson, 1992). It is likely that the nonacrophobic participants in this study predominantly experienced orientation reactions in the VE, whereas height exposure in the RE may have triggered a defense reaction, despite the low risk for a fall. Previous research in VE found a significant increase in both skin conductance and heart rate in nonacrophobic participants from a more stressful height exposure (Meehan et al., 2003). Because of safety concerns, the current study did not consider more dangerous height exposures.

The standing balance results demonstrate that using a VE in a SSVR system is relevant for simulating the destabilizing effects of height. The comparable postural instability at height in the RE and VE reflects a similarly reduced potential for visual stabilization, which is best

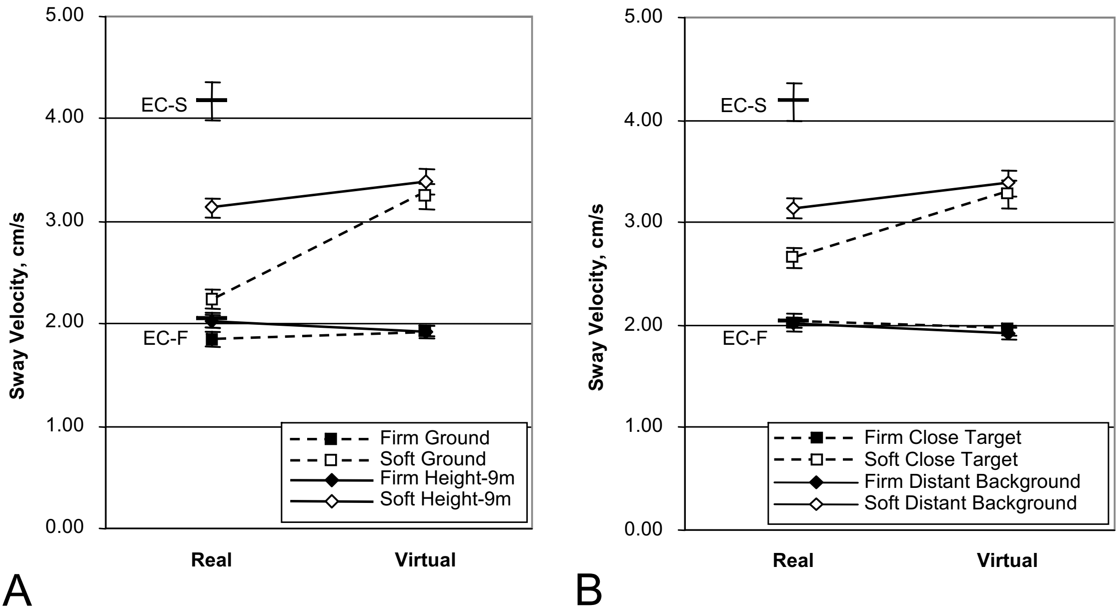

Figure 5. Interactions of (a) visual environment, height, and surface firmness and (b) visual environment, close visual target, and surface firmness on velocity of sway. EC-S = eyes closed, soft support; EC-F = eyes closed, firm support.

revealed under unstable support conditions. The increased postural instability in the VE as compared with the RE at the ground level, and with a close visual target, further indicates that in general the VE does not provide a reliable visual frame of reference. Postural instability in VE has been related to a number of factors, including low image resolution, system lag, and tracking inaccuracies (Kolasinski, 1995). Similarly, as with balance control at real height, maintaining posture in VE must rely exclusively on somatosensory and vestibular inputs (Keshner & Kenyon, 2000).

In summary, this study identified a number of similarities and differences between height effects in VE and RE. The similarities included perceived anxiety, skin conductance response, and postural instability. The differences included heart rate responses and perceptions of height distance and danger. Generalizing these findings may be limited by some of the following factors: the virtual model of elevation, the VR system, and the severity of simulated exposure. Different virtual models may not be equally effective in simulating height. This study used an enclosed environment of elevation that was rich in perspective cues. Previous research (Hodges et al., 1995) has shown that virtual models of elevation are more effective in inducing anxiety if they contain perspective depth cues. This study used a SSVR system in which the observers could see the screen edges and their own body and use them as a reference. Other VR systems, such as a head-mounted display system, completely isolate the visual field of the observer and may cause greater postural instability. The severity of height exposure (i.e., the level of danger) in this study was very mild and may preclude extrapolation of the results to more severe exposures.

CONCLUSIONS

The study results indicate that a simulation of elevated environment in an SSVR system is a valid tool in reproducing some of the psychological and physiological effects of height exposure. Virtual environments of elevation may find application in evaluation of different aspects of workers' behavior and performance during dangerous work at height and, in particular, the risk factors for loss of balance and fall initiation. Consequently, given the magnitude of the occupational fall injury problem, height simulations in SSVR may allow safe and time-efficient assessment of new fall prevention strategies.

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