The Influence of Restricted Viewing Conditions on Egocentric Distance Perception: Implications for Real and Virtual Environments

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Abstract

Three experiments examined the influence of field of view and binocular viewing restrictions on absolute distance perception in the real world. Previous work has found that visually directed walking tasks reveal accurate distance estimations in full-cue, real world environments to distances of about 20 meters. In contrast, the same tasks in virtual environments using head-mounted displays (HMDs) show large compression of distance. Field of view and binocular viewing are common limitations in research with HMDs and have been rarely studied under full pictorial-cue conditions in the context of distance perception in the real world. Experiment 1 determined that the view of one's body and feet on the floor was not necessary for accurate distance perception. Experiment 2 manipulated horizontal field of view and head rotation, finding that a restricted field of view did not affect the accuracy of distance estimations when head movement was allowed. Experiment 3 found that performance with monocular viewing was equal to that with binocular viewing. These results have implications for the information needed to scale egocentric distance in the real world and suggest that field of view and binocular viewing restrictions do not largely contribute to the underestimation seen with HMDs.

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An important problem in visual perception is how humans recover visual scale. In other words, how does the visual system determine the absolute size and distance of objects? Some perceptual measures suggest that humans are very good at solving this problem. A class of distance judgments characterized as *visually directed walking* tasks (Loomis, Da Silva, Fujita and Fukusima 1992), indicate that absolute distance estimations are performed accurately given full-cue environments in the real world. In these tasks, an observer first views a target and then attempts to walk to that target without vision. This spatial behavior is carried out without systematic bias within the range of *action space* (Cutting and Vishton 1995) up to about 20 meters (Loomis et al. 1992; Loomis, Da Silva, Philbeck and Fukusima 1996; Philbeck and Loomis 1997; Philbeck, Loomis and Beall 1997; Rieser, Ashmead, Taylor and Youngquist 1990; Thomson 1983). The present research examined the necessity of several viewing conditions in a well-lit environment for accurate egocentric distance perception as revealed through visually directed walking. A multitude of cues, both binocular and monocular, have been defined and examined with respect to their effectiveness for distance perception (Cutting and Vishton 1995; Gogel 1977). However, only a few cues (familiar size, angular declination, absolute motion parallax) can specify *absolute* distance within a range of "action space" and the effectiveness of these cues is unknown (Loomis and Knapp 2003). Furthermore, recent research using immersive virtual environments has consistently found compression of distance given full cues and visually directed action tasks (Durgin, Fox, Lewis and Walley 2002; Loomis and Knapp 2003; Thompson, Willemsen, Gooch, Creem-Regehr, Loomis and Beall in press; Willemsen and Gooch 2002; Witmer and Sadowski 1998). Thus, our goal was to investigate two types of viewing restrictions that have been rarely studied under full pictorial-cue conditions, and that are common limitations in research with virtual environments that use head-mounted displays (HMDs). We examined the necessity of a full field of view and binocular viewing for absolute distance judgments ranging from 2 to 12 meters in the real-world. Our findings that restrictions of field of view and binocular viewing did not influence the accuracy of distance scaling suggest that other factors may be contributing to the underestimation seen in virtual environments using HMDs.

Field of View

Humans normally experience a field of view (FOV) of approximately 200 degrees horizontal and 135 degrees vertical given binocular viewing without moving the eyes and head (Wandell 1995). Several lines of research suggest that restricting different aspects of field of view might influence perception of space. First, seeing the ground and one's body and feet on the ground emerges as an important consideration for absolute egocentric distance perception. Sinai, Ooi and He (1998) demonstrated that the surface of the ground is used as a reference frame for judging absolute distance, consistent with ideas of Gibson (1950). They found that a continuous ground surface was important for accurate distance judgments. In several manipulations, they disrupted continuous and homogeneous ground surface information and found impairments in distance estimations. One study created a gap in the ground surface and placed an object on the other side of the gap. Both visually directed actions and conscious perceptual estimations of distance were overestimated. They found that observers overestimated their eye height with respect to the ground surface of the gap, an explanation consistent with the resulting overestimation of distance. In a second study, the authors manipulated texture gradient information of the surface by using a ground surface that began as concrete and became a grassy field. Distances to targets were viewed across the two surfaces. Absolute distance was underestimated compared to conditions in which the ground was a homogeneous concrete or grassy surface.

Viewing the ground under one's body could also contribute to a more accurate sense of eye height from the ground, which has been shown to be important for scaling size and distance (Mark 1987; Warren and Whang 1987; Wraga 1999). Recent work suggests that *angular declination* serves as a strong cue to distance given that one is standing on the ground plane and has information about eye height (Ooi and He 2001; Philbeck and Loomis 1997). Angular declination is the angle between a visual target and an observer's eye level. Ooi and He (2001) provided evidence that the human visual system uses angular declination for egocentric distance judgments to targets on the ground with a series of studies using prisms. First, in a well-lit environment, they introduced prisms that deviated light so that angular declination increased, and found underestimations in visually directed action judgments. In a prism adaptation study, they found that walking or throwing while wearing these prisms for 20 minutes led to overestimations in a blindwalking post-test. These results are consistent with the notion that observers adapted to a decreased perceived eye level which would lead to a reduced angular declination and thus, an overestimation of distance. They also conducted a series of experiments in the dark to confirm that eye level and angular declination, and not other cues in a rich environment, predict perception of distance. The results were consistent with the full-cue studies. Visually perceived eye level and target locations were influenced by the prism manipulation.

In addition to evidence in the real-world that the ground plane and perceived eye level influence distance perception, the striking difference between distance estimations in real and HMD environments has led to the claim that field of view (both vertical and horizontal) matters. Several studies now have demonstrated underestimations in distance estimations in virtual environments, although the size of the effect has varied (Knapp 1999; Thompson et al. in press; Witmer and Kline 1998; Witmer and Sadowski 1998). In most studies with virtual environments using HMDs, an observer's body is not rendered in the environment and the viewer experiences a severely reduced horizontal field of view. For example, recent studies of Thompson et al. (in press) assessed whether the quality of graphics mattered for accurate distance perception in virtual environments using graphical and photographic panoramas. Since the environments lacked a view of the floor and the viewer's feet, Thompson et al. required observers to wear a circular collar that occluded the ground below them. They used an HMD with a 42 degree horizontal field of view. They presented targets on the ground in a large lobby ranging from distances of 5 to 15 meters and used a triangulated walking task in which observers viewed a target, then walked obliquely without vision, and given a signal, turned to face the target. The results indicated approximately 50% compression of distance in all of the virtual environments compared to near perfect performance in the same space in the real world.

One common account for this apparent compression of space in HMD environments is a restricted horizontal field of view that influences the amount of peripheral visual information available (Kline and Witmer 1996; Psotka, Lewis and King 1998; Witmer and Kline 1998; Witmer and Sadowski 1998). A number of studies with virtual environments have indicated inferior performance on a variety of tasks with smaller horizontal fields of view (Arthur 2000). Many of these tasks have involved visual search, walking, or spatial orientation judgments after turning using large projection screens, HMDs, or flight simulators (Piantanida, Boman, Larimer, Gille and Reed 1992; Riecke, Van Veen and Bulthoff 2002; Riecke, von der Heyde and Bulthoff 2001; Wells and Venturino 1990). Arthur (2000) found performance decrements associated with a smaller field of view in virtual environments in a search task and a walking task, but not in tasks involving egocentric distance perception or spatial memory. In the real world, several studies suggest that the world appears smaller with field of view restrictions (Alfano and Michel 1990; Dolezal 1982; Hagen, Jones and Reed 1978), however some direct tests of egocentric distance perception have found little differences between restricted and unrestricted conditions (Knapp and Loomis in press). The present studies indirectly address the question of the influence of field of view restrictions in virtual environments by creating conditions in the real-world that are analogous to constraints in HMDs. We examined two specific types of field of view restrictions: the inability to see one's own body and feet directly on the ground plane, and a smaller than normal horizontal field of view.

Binocular Viewing

A wealth of research has examined the effectiveness of binocular viewing on distance perception (Foley 1980; Gogel 1977). Accommodation and convergence have been shown to be effective cues at distances less than 2 meters when consistent with each other (Gogel 1961). Binocular disparity as a cue to depth is also most effective for near spaces (see Cutting and Vishton 1995). Binocular disparity provides information about relative depth but when paired with convergence, can provide absolute scale information. Studies examining the effects of binocular viewing using targets in reduced-cue environments have found little influence of binocular information on distance perception beyond short distances. For example, in a series of studies, Philbeck and Loomis (1997) presented targets at distances ranging from 1 to 5 meters, on the floor and at eye level, and found no difference between monocular and binocular viewing for all distances. A question exists, however, about the relevance of binocular information beyond 2 meters in full pictorial-cue environments. It is possible that effects of binocular disparity and the pairing of accommodation and convergence for near distances could provide information for scaling farther distances. Wu et al. (2003) have suggested that cues for the near ground surface are important for perceiving farther distances. This question is especially relevant given the known problems with creating accurate stereoscopic viewing in HMDs (Wann, Rushton and Mon-Williams 1995). The normal coupling between accommodation and convergence in the real world is disrupted with HMDs because of the fixed effective viewing distance. Other distortions are likely to occur because of the optics of the display. If binocular viewing matters for the accuracy of distance estimation at farther distances in a well-lit environment then problems with stereoscopic viewing in HMDs could contribute to the apparent compression of space. To address this concern, our third experiment examined the importance of binocular viewing in our visually directed walking task.

Overview to Studies

We conducted three experiments that examined the influence of field of view and binocular viewing on real-world egocentric distance perception under full pictorial cue conditions. Participants viewed a target on the floor at distances ranging from 2 to 12 meters and attempted to walk without vision to the target. Experiment 1 restricted viewing of the observer's body and the floor within about 1.5 meters of where they were standing. Experiment 2 restricted horizontal field of view to 42 degrees (32 vertical), and manipulated whether the head was free to rotate. Experiment 3 compared monocular and binocular viewing. When participants were free to rotate their heads, limitations of viewing their feet and the floor, horizontal field of view, and monocular viewing all resulted in little difference in performance compared to the completely full-cue conditions.

Experiment 1: Restricting vision of the ground and feet

Both real- and virtual-world findings led us to question the influence of the view of an observer's own feet and the ground under their feet on absolute distance estimations. Several studies point to the importance of viewing a continuous ground plane and eye height as a scaling cue for size and distance (Ooi & He 2001; Sinai et al. 1998; Wraga 1999). The view of an observer's own body is most often missing while viewing an environment through an HMD and some have suggested that seeing a "virtual body" increases a sense of *presence* and may contribute to spatial awareness (see Draper 1995). The present experiment asked whether viewing one's feet and the ground under one's body and feet is necessary for accurate distance scaling in the real-world.

Method

Subjects

Twenty-three participants (11 male) from the University of Utah community participated in partial fulfillment of a course requirement or for compensation of $10. All participants had normal (20/20) or corrected to normal acuity and normal stereo vision, determined by pre-testing before the start of the experiment. None had participated in a distance study before, and all were naive to the design and predictions of the experiment.

Design

We used a 2 (restriction) x 2 (sex) x 6 (distance) factorial design in which viewing restriction and sex were between-subjects variables and distance was a within-subjects variable.

Stimuli and Apparatus

A cardboard circular collar (56 cm diameter with 20 cm diameter neck hole) was created that rested on two foam cubes at the front and back (see Figure 1). The collar occluded vision of the participant's body and the floor below their feet to about 1.5 meters. The experiment was performed in a wide hallway of an engineering building (see Figure 2). The target stimulus was a foam-core circular disk (37 cm diameter) placed on the ground.

Procedure

Participants were provided both written and verbal instructions about the task. They were given approximately 5 minutes of practice walking without vision in which the experimenter verbally instructed the participant to start and stop walking and to turn. This practice was intended to build trust between the participant and the experimenter and to familiarize the participant to walking without vision. In all conditions, participants wore headphones that introduced broadband masking noise to minimize auditory distance cues. The headset was also connected to a wireless microphone that allowed participants to binaurally hear instructions from the experimenter. Participants were instructed to face the target and to form a "good image" of the target and the hallway surroundings. They were encouraged to rotate their head to look to the sides of the hallway as well as the target in front of them. When ready, they were instructed to cover their eyes with a blindfold and to walk purposely and decisively to the target without vision, visualizing the environment as they walked through it. One experimenter walked next to the participant to ensure that they would not walk into a wall. A second experimenter removed the target before the participant approached. The distance walked from the starting position to the participant's stopping position was measured. The participant was then walked back to the starting position in an indirect path while they remained blindfolded.

Participants performed in one of two conditions, blind-walking while wearing the occluding collar, and blind-walking under full-cue conditions. The target was placed at distances of 2, 3.5, 5, 8, 10, and 12 meters. Each distance was repeated three times.

Results and Discussion

Distance walked while wearing the collar did not differ from the no-collar condition. In both conditions, performance was close to accurate (see figure 3). A 6 (distance) x 2 (collar) x 2 (sex) mixed ANOVA was performed on the mean distance walked. Distance was the only significant effect, $\underline{F}(5, 95) = 549.35$, $\underline{p} < .001$. Distance-walked increased linearly with actual distance to the target. The average distances walked were fit well by a linear function for each condition. The slopes for collar and no-collar conditions were .98 and .93, respectively, $\underline{R}^2 = .99$ for both conditions. Variable error (within-subject variability) was also assessed for each condition by calculating the standard deviation of the mean of three trials for each distance for each subject. A 6 (distance) x 2 (collar) ANOVA was performed on the mean variable error and again the only significant effect was distance, $\underline{F}(5, 105) = 13.439$, $\underline{p} < .001$. Variable error increased with increasing distance, but did not change as a function of wearing the occluding collar.

In all, the present experiment demonstrated that there was no effect of wearing the occluding collar on accuracy of distance judgments. These results indicate that given otherwise full-cue conditions, viewing the ground that one is standing on is not necessary for accurate distance scaling. These findings do not necessarily negate the importance of eye height for egocentric distance perception; rather they suggest that if eye height scaling is used, it does not require a view of the ground directly beneath one's body. Future studies that directly manipulate eye height and prevent viewing of the ground in real and virtual environments could help to address this question. It is also possible that viewing a continuous ground plane would be more important when other visual information is missing. A recent study by Wu, He, and Ooi (2003) found that distance judgments were underestimated when viewers were prevented from pitching their head to look down at the floor only when their horizontal field of view was smaller than 30 degrees.

Experiment 2: Restricting horizontal field of view

Experiment 1 demonstrated that seeing the ground and one's feet on the ground was not necessary for accurate distance judgments. In our next study, we examined the restriction of horizontal field of view. There are mixed experimental results about the importance of a large horizontal field of view for accurate egocentric distance perception. We might expect a restricted FOV to have a detrimental effect on spatial judgments because of its diminishing effect on peripheral information used in spatial behavior (Dolezal 1982). A FOV restriction could work to reduce environmental context and texture gradient information, and to form an artificial frame around the world. When FOV has been manipulated in real-world distance studies, some have found a compression of perceived distance (Dolezal 1982; Hagen et al. 1978) and size (Alfano and Michel 1990) while others have found little decrements (Knapp and Loomis in press) or decrements as a function of the extent of the restriction (Wu et al., 2003). Given that underestimation has now been found in a number of studies using HMDs and that HMDs typically have reduced FOVs, the restricted FOV has logically been proposed as a factor influencing distance perception (Witmer and Kline 1998; Witmer and Sadowski 1998). Using virtual environments, Kline and Witmer (1996)[1] and Psotka et al. (1998) found that manipulations of field of view size led to changes in distance estimations. FOV has been shown more consistently to have an effect on other types of spatial tasks such as visual search, walking, navigation, and spatial memory (Arthur 2000; Riecke et al. 2002; Riecke et al. 2001). Loomis and Knapp (2003) commented that one factor that has not been explicitly controlled for in FOV distance estimation studies has been the extent to which observers were free to rotate their head while in a restricted FOV setting (e.g., Kline and Witmer,1996). Wu et al. (2003) also found that head movement was important for accurate distance judgments when FOV was greatly reduced (less than 30 degrees). The present study involved three conditions that directly examined the influence of restricted FOV combined with head rotation on egocentric distance judgments in the real world. FOV was restricted to 42 degrees horizontal to be consistent with the FOV in the HMD used in our previous studies (Thompson et al. in press; Willemsen and Gooch 2002). Observers performed in one of three conditions: a full field of view, a restricted FOV in which they were free to rotate their head, and a FOV restriction along with a neck brace that restricted rotation and tilt of the head.

Method

Subjects.

Forty-eight students (25 male) from the University of Utah participated in partial fulfillment of a course requirement. All participants had normal (20/20) or corrected to normal acuity and normal stereo vision, measured before the experiment began. None had participated in a distance study before, and all were naïve to the design and predictions of the experiment.

Design

We used a 3 (restriction) x 2 (sex) x 5 (distance) factorial design in which viewing restriction and sex were between-subjects variables and distance was a within-subjects variable.

Stimuli and Apparatus

The target stimulus was the same as in Experiment 1. To restrict FOV, we used a pair of viewing goggles that constrained the participants FOV to approximately 42º horizontally by 32º vertically. Two pyramidal viewing cones were constructed from black foam-core board and mounted into a frame fitted with two worm gears to allow each goggle to move independently left and right. The frame slider mechanism was built from LEGOs and was designed to keep the viewing goggles in planar alignment, and to allow for changes in interocular distance between subjects. The viewing goggles were covered with black fabric to enclose the viewing cones and to eliminate light entering the device (see Figure 4). In one condition, we used a surgical neck brace that adjusted to the size of the neck with a Velcro strap to restrict head rotation and viewing of the feet and ground below one's feet (see Figure 4). The experiment was performed in a similar hallway as in Experiment 1, in the same engineering building.

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[1] Kline and Witmer (1996), however, found an overestimation of distance with a smaller FOV and underestimation with a larger FOV.

Procedure

The training and testing procedures were the same as in Experiment 1 except for the changes in the viewing conditions. Participants performed in one of three viewing conditions: full-FOV, restricted viewing goggles with free head rotation (FOV-rotate), restricted viewing goggles and restricted head rotation (FOV-no rotate). In the restricted conditions, participants were fitted with the viewing goggles and tested to ensure that their field of view was close to 42 degrees (plus or minus 1 deg). This test started by adjusting the viewing goggle's sliders to roughly match the interocular distance of the participant. The participants were then placed two meters from a poster with marks designating field of view increments. Participants were told to center themselves on the zero-degree mark of the poster and focus on that mark, viewing with both eyes. Working on one side of the zero-degree mark at a time, experimenters slowly moved a black rectangular marker in towards the zero-degree mark. Participants were told to indicate when the rectangular, black marker first appeared in their vision. Because a participant's FOV was also influenced by the distance of the viewing goggles to the participant's face, side-to-side adjustments in each goggle were often necessary to achieve a horizontal FOV of approximately 42 degrees. Experimenters repeated this process with both eyes until the participant's FOV closely matched the desired characteristics. The full-FOV and FOV-rotate conditions were performed as in Experiment 1. In the FOV-no rotate condition, participants viewed the target as in the other conditions, but they were prohibited from rotating their head to the right and left and up and down by the constraint of the neck brace.

Results and Discussion

Performance with the restricted viewing goggles did not differ from the full-cue condition when head rotation was allowed; both conditions demonstrated near-perfect performance. However, restricting head rotation led to underestimated distance judgments (see Figure 5). A 5 (distance) x 3 (restriction) x 2 (sex) ANOVA was performed on the mean distance walked with distance as a within-subjects variable and restriction and sex as between-subjects variables. The ANOVA indicated an effect of distance, $F(4, 168) = 870.92$, $p < .001$, restriction, $F(2, 42) = 8.41$, $p < .001$, and a distance x restriction interaction, $F(8, 168) = 2.61$, $p < .05$. Scheffe post hoc tests showed that the FOV-rotate condition was not different from the full-FOV condition ($p = .34$) and that the FOV-no rotate condition differed from both the full-FOV ($p < .001$) and the FOV-rotate ($p < .05$) condition. Estimations increased linearly with distance in all conditions. Figure 5 shows that the average distances walked were fit well by a linear function for each restrictor condition. The slopes for the full-FOV, FOV-rotate, and FOV-no rotate were .93, .92, and .78, respectively, $R^2 = .99$ for all conditions. Variable error (within-subject variability) was also assessed for each condition as in Experiment 1. A 5 (distance) x 3 (restriction) ANOVA was performed on the mean variable error and the only significant effect was distance, $F(4, 180) = 18.63$, $p < .001$. Variable error increased with increasing distance, but did not change as a function of viewing restriction.

Our results showed that given the freedom to rotate one’s head, a narrow horizontal field of view of 42 degrees did not impair distance estimations in the real world, supporting the findings of Knapp and Loomis (in press) and Wu et al. (2003). The FOV-no rotate condition directly addressed the question of whether decrements in performance that have been found in HMD distance estimation tasks (e.g. Kline & Witmer, 1996) could have resulted from the prevention of head movement. We found that when observers were prohibited from rotating their head, they underestimated distances. However, their inter-trial variability remained constant across conditions. These results suggest that distances were consistently perceived as closer without full information from the periphery gained through head movement.

The distinction between the lack of effect of FOV restriction (when head movement was allowed) in the present study and the compression seen in earlier studies of Hagen et al. (1978) and Dolezal (1982) could be a result of several methodological differences. Hagen et al. compared free monocular viewing with viewing through a peephole (2 mm), a rectangular truncation (4 x 6 cm), and photographic slides consistent with the truncated view, and assessed exocentric distances between two objects with a verbal-report task. Dolezal (1982) restricted FOV to 12 degrees with two viewing tubes, a much larger restriction than in the present studies. The effects found with greater FOV restriction are also consistent with Wu et al.'s (2003) recent findings that changes in performance were only seen with a FOV of 30 degrees or less when head pitch was not allowed. In all, Experiment 2 indicates that a full field of view is not necessary for accurate distance perception in the real world when head rotation is allowed and encouraged. Although we cannot make generalizations to restrictions greater or less than 42 degrees, we suggest that the common restriction of field of view in HMDs cannot account for the large compression effects found in virtual environment studies.

Experiment 3: Monocular and binocular viewing

Although much research has examined the utility of binocular vision for depth perception, studies have focused on near distances or reduced-cue environments. We were especially interested in examining a full-pictorial cue environment because of puzzling compression seen in virtual environments given full-cues. There are a number of problems inherent in creating stereoscopic depth in virtual environments using HMDs (Wann et al. 1995). Fixed viewing distance to the graphical display leads to accommodation-convergence rivalry. Additional problems arise due to optical properties of these displays, which have the potential to distort binocular disparity in a variety of ways. It is possible that these problems have contributed to the depth compression seen in previous studies. One way of addressing this problem is to vary the binocular information in the HMD itself (Willemsen, Gooch, Thompson and Creem-Regehr 2003). Willemsen et al. (2003) found no difference in distance judgments for binocular, bi-ocular, or monocular viewing in an HMD. All viewing conditions and distances were similarly underestimated. An alternative approach is to assess whether distance judgments are affected by restrictions of binocular viewing in the real world. Experiment 3 took this approach and asked observers to walk without vision after monocular viewing of distances to targets on the ground.

Method

Subjects

Sixteen volunteers (8 male) were tested on the monocular viewing condition. All participants had normal (20/20) or corrected to normal acuity and normal stereo vision. None had participated in a distance study before, and all were naïve to the design and predictions of the experiment.

Design

We used a 2 (restriction) x 2 (sex) x 5 (distance) factorial design in which viewing restriction (monocular versus binocular) and sex were between-subjects variables and distance was a within-subjects variable. The full-FOV condition from Experiment 2 was used as the binocular control condition in the present experiment.

Stimuli

The target and hallway were the same as in Experiment 2. An eye-patch was used to cover the participant's non-dominant eye.

Procedure

The same general procedure was used as in Experiments 1 and 2. Participants were tested for eye dominance and wore an eye patch over their non-dominant eye throughout the entire experiment.

Results and Discussion

There was no difference in performance between the monocular and binocular viewing conditions. A 5 (distance) x 2 (restriction) x 2 (sex) ANOVA was performed on the mean distance walked with distance as a within-subjects variable and restriction and sex as between-subjects variables. The only significant effect was of distance, $\underline{F}(4, 116) = 537.92$, $\underline{p} < .001$. Figure 6 shows that the average distances walked were fit well by a linear function for both viewing conditions. The slopes for the binocular and monocular conditions were .93 and .96, respectively, $\underline{R}^2 = .99$ for both conditions. Variable error was also assessed for each condition as in the previous experiments. A 5 (distance) x 2 (restriction) ANOVA was performed on the mean variable error and the only significant effect was distance, $\underline{F}(4, 124) = 11.75$, $\underline{p} < .001$. Variable error increased with increasing distance, but did not change as a function of monocular or binocular viewing.

Consistent with studies in real-world reduced-cue environments, binocular viewing had little effect on the accuracy of distance judgments in action space. These results address the question of whether accommodation, convergence, and binocular disparity as near depth cues might contribute to perception of farther distances in a full-pictorial cue environment. Wu et al. (2003) have proposed a sequential surface integration process hypothesis in support of the importance of the near ground surface in space perception. This hypothesis suggests that near depth cues are used to construct an initial ground surface representation and then adjacent surfaces are constructed using optical slant information, and integrated with the initial framework of the ground surface. In their study, given monocular viewing and restricted field of view, when participants were prohibited from scanning the ground, distance estimations were underestimated. The performance seen in the present studies suggests that there is enough monocular depth information (e.g. texture gradient, linear perspective) in the environment when field of view is not restricted that binocular depth cues are not needed for accurate distance perception. The accurate performance lends support to the claim that imperfect stereoscopic depth cues in HMDs are not a large contributor to the compression effect.

General Discussion

Three experiments investigated the influence of restrictions of field of view and binocular vision on visually directed walking tasks in full pictorial-cue environments. These studies were partially motivated by the claims of several studies involving distance perception in virtual environments that restrictions associated with the technical limitations of HMDs contribute to decrements in distance scaling. Our studies examined some of the most common restrictions found in HMDs—the missing view of the observer's feet, a reduced horizontal field of view, and imperfect stereoscopic viewing—by constructing analogous conditions in the real-world. In all, we found that if observers were encouraged to look around, none of the restricted viewing manipulations had a negative effect. Walking without vision remained accurate at all distances tested. These results have implications both for the cues that are necessary for absolute distance perception in the real world, and the factors involved in creating veridical perception of space in virtual environments.

Absolute distance perception in a well-lit environment

Egocentric distance perception has been investigated with respect to the contribution of binocular and monocular cues at ranges of near to far distances (Cutting and Vishton 1995), and the extent to which different measures of perceived distance reflect perceived distance (Loomis et al. 1992; Philbeck and Loomis 1997). The examination of cues for different ranges of distances has a long history, much of which has focused on reduced-cue environments. The logic of studying reduced-cue environments is to isolate and test a certain cue by making other cues unavailable to the visual system. A number of elegant studies have demonstrated that cues of accommodation, convergence, binocular disparity, and motion parallax are weak cues to absolute egocentric distance beyond 2 meters (Beall, Loomis, Philbeck and Fikes 1995; Gogel 1961; 1977; Philbeck and Loomis 1997). However, angular declination scaled by eye height has been shown to be a stronger cue (Ooi et al. 2001; Sinai et al. 1998; Philbeck and Loomis 1997). We chose to manipulate our viewing restrictions in a well-lit environment to examine analogous restrictions that are faced in high-quality simulated environments using HMDs. Since underestimation of space has consistently been found in virtual environments, we asked whether simply limiting the same information in the real-world would lead to similar underestimation of distance. For this reason, restrictions of field of view and binocular viewing were implemented in otherwise full-cue environments. Although this method does not allow claims about the importance of isolated cues for distance, it can suggest whether cues are necessary given the combination of other cues present. Thus, given full-pictorial cues and free head rotation, we found that field of view restrictions and monocular viewing did not influence distance judgments to targets on the floor in a range of action space.

It is also important to consider the measure used to reveal perceived distance. The present studies used a visually directed walking task shown in a number of studies to result in accurate indications of target distance (Loomis et al. 1992; Rieser et al. 1990; Steenhuis and Goodale 1988; Thomson 1983). However, several studies have found that other measures such as verbal reports and perceptual matching (Loomis et al. 1992; Loomis et al. 1996) indicate compression of space that increases with farther distances. Some have considered the possibility that different types of measures of perceived distance reveal either a visuomotor calibration relating perceived distance to action (Loomis et al., 1992) or different underlying representations for perception and visuomotor control (Creem and Proffitt 1998; Goodale and Milner 1992). Evidence against the calibration account comes from visually directed action measures that do not involve directly walking to a target. For example, researchers have found accurate performance using measures that involve triangulation by walking, or triangulation by pointing, that require observers to begin walking on an oblique path and then given a cue, turn to face the target (Fukusima, Loomis and Da Silva 1997; Loomis et al. 1992; Philbeck et al. 1997; Thompson et al. in press). Although there is support in a number of domains for a model of visual processing that defines separate functional pathways for perception and action, some research suggests that visually directed walking and verbal reports are both controlled by the same representation of perceived distance (Philbeck & Loomis, 1997; Philbeck, Loomis & Beall, 1997). These studies found that manipulating a given stimulus cue had the same influence on both verbal and walking measures of perceived distance. We used a single measure of direct walking to targets without vision because of the established accuracy and small variability associated with this task under full-cue conditions. Although we might predict similar results as those found in the present studies when using other measures of perceived distance in the real world, this still remains an open question.

Distance underestimations in virtual environments: Viewing restrictions an unlikely account

One goal of the present studies was to examine two common accounts of compression in HMDs—a limited field of view and imperfect stereoscopic viewing. Knapp (1999) and Thompson et al. (in press) both found greater than 50% underestimation of distances ranging from 1 to 20 meters. Thompson et al. (in press) found these results with a triangulated walking task, whereas Knapp (1999) compared verbal, walking, and a size-based measure. Our restrictions of field of view and binocular viewing in real-world settings suggest that it is unlikely that these viewing conditions can fully account for the large distance compression seen in virtual environments. We found that a field of view greater than 42 degrees, seeing one's own body and feet standing on the ground, and binocular viewing were unnecessary factors for accurate distance perception in the real world.

One way to further test these potential viewing factors would be to directly manipulate them in the HMD. Willemsen et al. (2003) took this approach to investigate contributions of stereoscopic viewing to distance perception in HMDs. Based on the knowledge that there are imperfections in creating stereoscopic depth in HMDs, they compared binocular, bi-ocular, and monocular viewing of targets in a virtual environment. Observers viewed targets on the ground at a range of 5 to 15 meters and performed a triangulated walking task to estimate distance. Their results indicated consistent compression of space in the HMD conditions compared to the real-world consistent with previous studies, but there was no difference among viewing conditions.

Investigations of FOV have also been examined with manipulations in virtual environments, although most of these studies have focused on spatial tasks other than distance perception. Arthur (2002) examined performance on several spatial tasks using an HMD with a maximum of 176 degree horizontal (47 degree vertical) FOV. He compared 48, 112, and 176 degree FOVs using the same HMD. FOV had a significant effect on search and walking tasks; a wider FOV led to faster performance. Other HMD studies have found similar effects on search and spatial navigation tasks (Cunningham, Nelson, Hettinger, Haas and Russell 1996; Piantanida et al. 1992). However, others have found that screen curvature may be more important than FOV for accurately perceiving ego-rotations (Schulte-Pelkum, Riecke and von der Heyde 2003; Schulte-Pelkum, Riecke, von der Heyde and Bulthoff 2002). Schulte-Pelkum and colleagues had observers view optic flow information on a flat or curved display screen (86 x 64 deg), with or without blinders that reduced the FOV to 40 x 30 degrees to be consistent with viewing through an HMD. They found that turning performance was significantly worse for the HMD condition, but that there was no difference between viewing a large screen with or without restricting blinders. There was also improved performance with a curved compared to a flat screen.

Given the present results, the question of what is contributing to the distance underestimations found in virtual environments still remains. We have made recent efforts to identify the factors that may be important to perceive accurate scale in virtual environments. One factor examined has been the quality of graphics. Thompson et al. (in press) created three variations on the realism of graphics presented in an HMD. They compared distance estimations to targets on the ground in impoverished graphics environments to realistic photographic panoramas and the real world. Distance estimations, although near perfect in the real world, were equally compressed in all of the HMD environments. Despite these empirical results, subjective sense of scale in the photorealistic environments seemed greater. It is possible that other types of measures of distance or scale would lead to different results. Future studies are needed to study the interaction between quality of graphics and measures of perceived distance. Other differences between distance estimations in the real-world and in HMDs might relate to the ergonomics of acting with the HMD itself, rather than the nature of the FOV restriction. Ongoing studies are examining this possibility.

In all, the present studies demonstrate that human perception of absolute distance in a well-lit environment remains accurate when field of view or binocular viewing is restricted. Our results in the real-world suggest that these viewing restrictions are not a dominant cause of distance compression seen in HMDs. Future research may examine the compression effect found in HMDs further by manipulating visual and non-visual cues and task measures in both real and virtual environments.

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Figure Captions

Figure 1. A participant wearing the occluding collar used in Experiment 1.
Figure 2. The hallway setting used in Experiments 1-3.
Figure 3. Mean distance walked (+/- 1 SE) as a function of actual distance for the collar and no-collar conditions in Experiment 1.
Figure 4. The FOV restricting goggles (a) and neck brace (b) used in Experiment 2.
Figure 5. Mean distance walked (+/- 1 SE) as a function of actual distance for the full-FOV, FOV-rotate, and FOV-no rotate conditions in Experiment 2.
Figure 6. Mean distance walked (+/- 1 SE) as a function of actual distance for the monocular and binocular viewing conditions in Experiment 3.

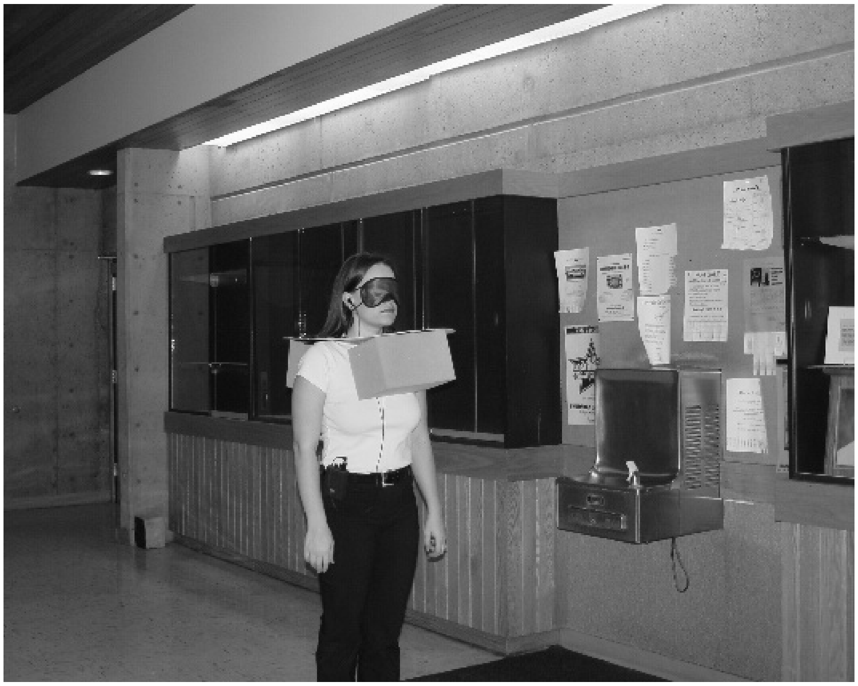

Figure 1

Figure 2

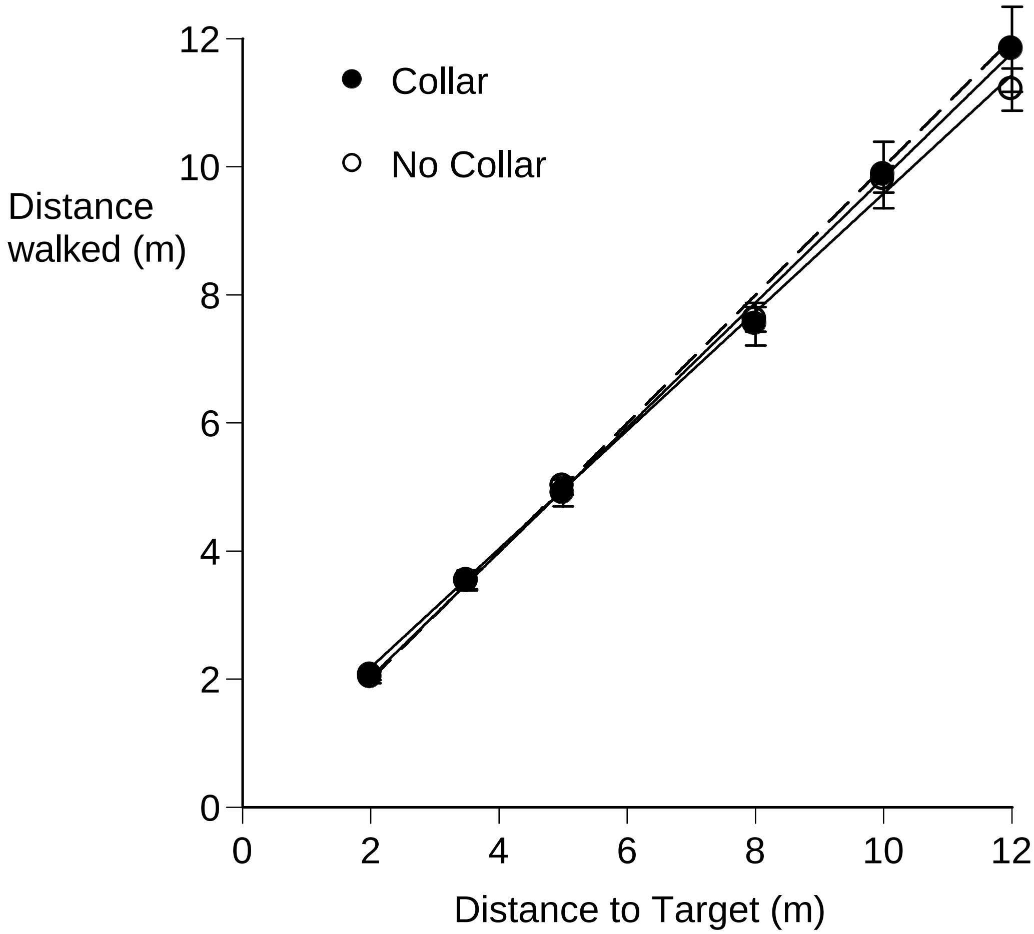
Collar
No Collar
Distance walked (m)
0
2
4
6
8
10
12
0
2
4
6
8
10
12
Distance to Target (m)

Figure 3


a


b

Figure 4

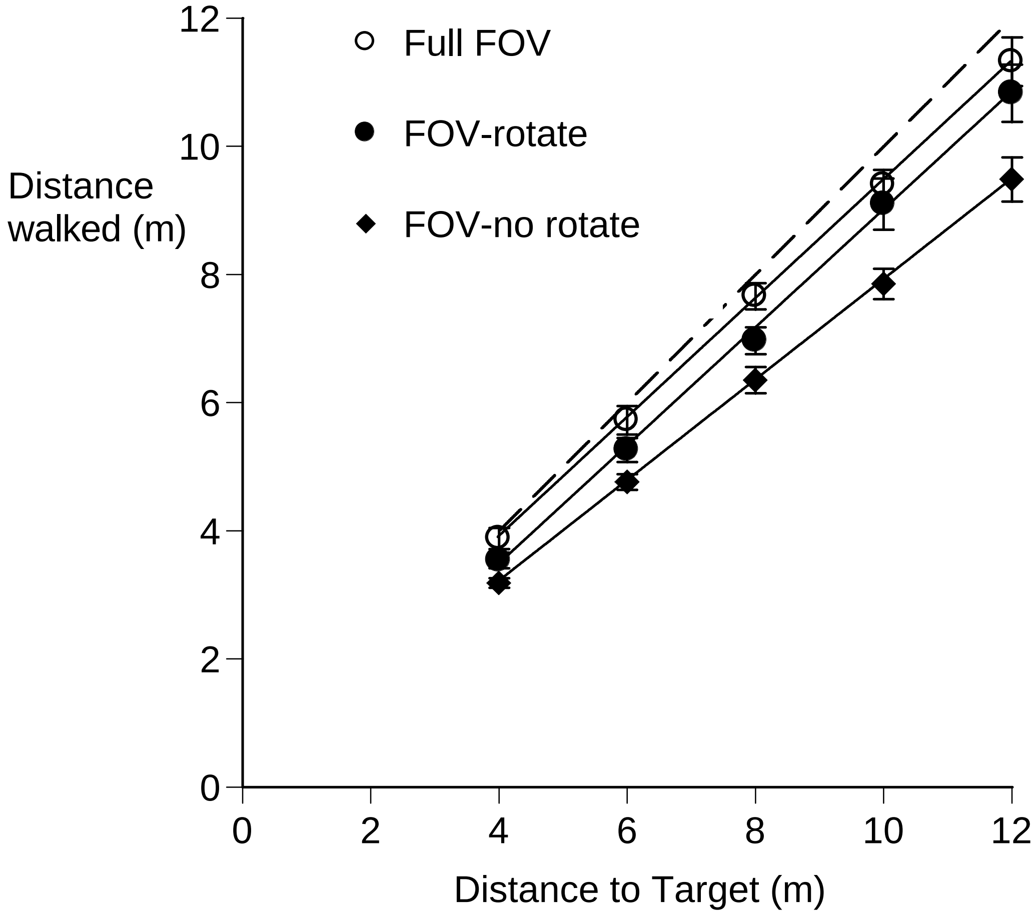
Full FOV
FOV-rotate
FOV-no rotate
Distance walked (m)
0
2
4
6
8
10
12
Distance to Target (m)

Figure 5

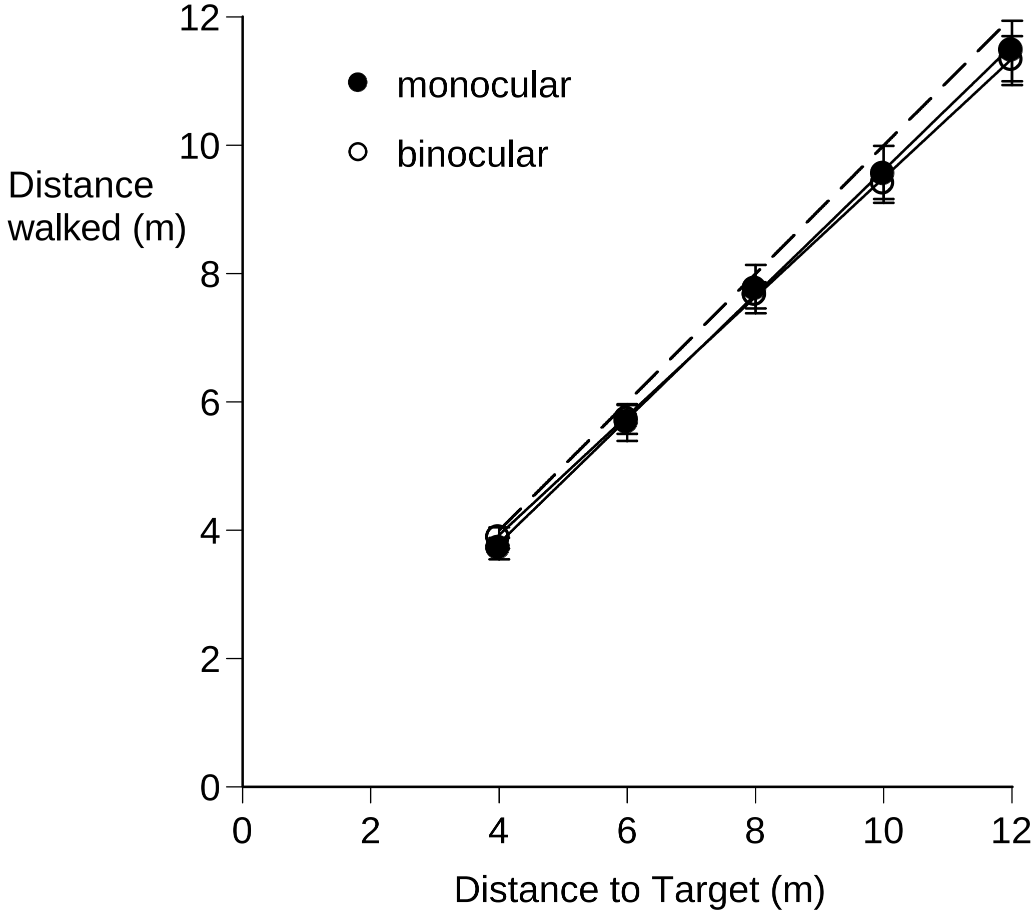
monocular
binocular
Distance walked (m)
Distance to Target (m)
0
2
4
6
8
10
12

Figure 6