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# Effects of Stereo Viewing Conditions on Distance Perception in Virtual Environments

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**Abstract**

Several studies from different research groups investigating perception of absolute, egocentric distances in virtual environments have reported a compression of the intended size of the virtual space. One potential explanation for the compression is that inaccuracies and cue conflicts involving stereo viewing conditions in head mounted displays result in an inaccurate absolute scaling of the virtual world. We manipulate stereo viewing conditions in a head mounted display and show the effects of using both measured and fixed inter-pupillary distances, as well as bi-ocular and monocular viewing of graphics, on absolute distance judgments. Our results indicate that the amount of compression of distance judgments is unaffected by these manipulations. The equivalent performance with stereo, bi-ocular, and monocular viewing suggests that the limitations on the presentation of stereo imagery that are inherent in head mounted displays are likely not the source of distance compression reported in previous virtual environment studies.

**I Introduction**

Subjective experience and empirical research suggest that there are differences between human perception in real and virtual environments. Understanding the specific nature of these differences and why they occur are important questions for virtual reality researchers. Several research groups have reported that when participants judge absolute egocentric distances using a visually directed action in a head mounted display (HMD), they tend to underestimate the intended distances. However, when these same tasks are performed in a real environment, participants direct their actions accurately. These studies have investigated many of the issues that have potential for affecting distance judgments in virtual environments, including the effects of field of view (Creem-Regehr, Willemsen, Gooch, & Thompson, 2005; Knapp & Loomis, 2004), graphics quality (Thompson et al., 2004), and HMD mass and inertia (Willemsen, Colton, Creem-Regehr, & Thompson, 2004). Unfortunately, the cause of the compression is still unknown.

The present research investigates whether the compression of space in virtual environments specifically stems from differences in stereo viewing conditions be-

tween real and HMD environments. In particular, we are interested in understanding the effectiveness of stereo viewing in an HMD as it pertains to judging distances to targets out beyond a couple of meters. Our experiments suggest that for targets on the ground plane out to 15 m, inaccuracies in stereo viewing conditions inherent in HMDs are not likely the source of compression.

The result that people tend to act as though the world is smaller than intended is quite surprising given the accuracy with which people judge similar distances under real viewing conditions. This paper specifically focuses on the effectiveness of stereo viewing in HMDs and how it may relate to judging distances within a virtual environment. In the present study, we varied the presentation of stereo information in an HMD to provide either monocular, bi-ocular, binocular with fixed IPD, or binocular with measured IPD viewing conditions. An additional condition compared the effects of stereo and monocular viewing on egocentric distance judgments in the real world. Distance judgments were obtained using a visually directed action in which participants first viewed the target and then walked without vision toward the target. The stereo viewing manipulations ranged from traditional stereo viewing with an HMD to monocular viewing conditions, in which any accommodation-convergence mismatch in the HMD would be minimized. One hypothesis we attempted to test was whether reducing the mismatch between accommodation and convergence, as experienced in the monocular viewing of the environment, would result in more accurate distance judgments.

Indications of distance were similar across stereo, bi-ocular, and monocular viewing conditions in the HMD. Even in the real world conditions, monocular viewing produced no deficits in performance. These results suggest that the amount of compression observed in previous studies is not affected by the limitations of presenting stereo imagery in HMDs.

## 2 Background and Related Work

Human perception research from the psychology and vision science communities is increasingly useful to

researchers in computer graphics and virtual environments. Our work combines efforts from these areas to understand how humans perceive space and interact with virtual environments.

Perceptual psychology research has investigated the relationships between perception, representation, and action in terms of spatial updating and locomotion in a physical environment (Rieser, Ashmead, Taylor, & Youngquist, 1990; Thomson, 1983). To understand these relationships, researchers have used visually directed actions, such as blind walking to previously viewed targets, as response measures for how physical space maps to perceived visual space (Loomis, Da Silva, Fujita, & Fukusima, 1992; Philbeck, Loomis, & Beall, 1997; Fukusima, Da Silva, & Loomis, 1997). In these studies, participants are first allowed to view targets and then asked to walk without vision to the location of the perceived target either in a direct or indirect manner. The results indicate that in real world hallways and outdoor spaces under full cue conditions, people are accurate at judging distances to targets resting on the ground out to about 25 m. The distance judgments acquired in these studies represent a particular type of absolute distance judgment based on an egocentric perspective, and are meant to retrieve a measure of the absolute, scaled distance between an observer and an external target. It is important for the purposes of the experiments presented later to make a differentiation between both egocentric and exocentric distance judgments along with relative and absolute distance judgments. Egocentric distances are distances from an observer to an external target. Exocentric distances are distances between two objects external to an observer. Relative distance measurements provide a description of spatial layout up to an unknown scale factor. Absolute distance measurements provide a scaled description of distance based on some metric quantity, such as feet or arm lengths. In our work, we specifically combine the egocentric and absolute terms to describe a distance measurement of absolute scale between an observer and an external target.

Other research efforts have investigated the effectiveness of different cues for distance perception. Most visual cues provide only relative or ordinal depth informa-

tion, while a select few can provide scaling information necessary to recover absolute depth. Absolute depth cues include familiar size, motion parallax, angular declination when combined with viewing height, accommodation, and convergence. Cues such as binocular disparity, relative size, the horizon ratio, texture gradients, shading, and occlusion, by themselves provide relative or ordinal depth information. Under appropriate circumstances, accommodation, convergence, motion parallax, and familiar size can provide correctly scaled distance information. On their own, binocular disparity and relative size provide information only about the relative distance between two environmental locations. The same is true of the depth cues arising from linear perspective, such as angular declination, the horizon ratio, and texture gradients. However, when combined with information about the viewing height, angular declination has the potential to indicate absolute depth.

The amount to which these cues influence perception varies with distance. For space perception, Cutting and Vishton (1995) have found it useful to divide the environment around an observer into distance classifications: personal space (within arm's reach), action space (2–30 m), and vista space (beyond 30 m). Within action space, accommodation, convergence, and motion parallax are considered to be weak cues for absolute distance (Beall & Loomis, 1995; Gogel, 1961) as their individual effects tend to diminish out past 2 m. However, absolute depth beyond 2 m can be recovered from binocular disparity by using convergence as a scaling factor (Foley, 1980). Moreover, there is evidence that near distance ground surface cues are important for perceiving farther distances. Such angular declination cues can be used to recover absolute distance given a known eye height (Wu, Ooi, & He, 2004).

With an HMD, technological limitations make precise presentation of these visual cues problematic. In particular, presenting stereo information accurately in HMDs is difficult (Wann, Rushton, & Mon-Williams, 1995). Collimated optics in HMDs create a fixed viewing distance to the image plane and force accommodation to be constant, creating an accommodation-convergence mismatch. Under normal vision, accommodation and convergence are linked together tightly (Gogel, 1961).

Binocular disparity is susceptible to distortions caused by the optics used in HMDs. While inter-pupillary distance (IPD) is important for viewing at near distances, it is difficult to match exactly in most HMDs (Robinett & Rolland, 1992). Due to the lack of precise control over image position, IPD can only roughly be controlled. HMDs allow user adjustment of IPD and position on the head, but do not allow a means to read back the actual distance between the centers of the screens within the HMD. The same issue affects knowing the actual accommodative distance in HMDs with some HMDs even allowing user adjustment of focus. Almost always, calibrated information about the actual accommodative distance in a particular HMD cannot be obtained. While incorrect accommodation is known to affect distance judgments (Bingham, Bradley, Bailey, & Vinner, 2001), conducting controlled studies of accommodation within an HMD are nontrivial due to both the difficulty in determining the actual accommodative distance in a particular HMD and the difficulty in inserting lenses between the eyepieces of the HMD and the user's face to change this accommodative distance.

At near distances, stereo viewing with HMDs has been shown to be effective for matching and placement experiments. Users' actions are generally more accurate with stereo viewing, whereas monocular viewing in these situations resulted in less accurate matching and placement of objects (Surdick, Davis, King, & Hodges, 1997; Hu, Gooch, Creem-Regehr, & Thompson, 2002; Ellis & Menges, 1997). Additionally, the effectiveness of stereo viewing for disambiguating wireframe images can differ between a static situation, in which stereo is most effective, and a similar dynamic situation, where it is less effective, as compared with monocular viewing (Doshier, Sperling, & Wurst, 1986). Experiments investigating manual pursuit tracking have shown that stereo viewing of an environment reduced tracking errors over a monocular viewing of the environment (Kim, Ellis, Tyler, Hannaford, & Stark, 1987). Similar improvements were obtained for relative depth ordering judgments and cursor placement in a 3D display system (Reinhart, Beaton, & Snyder, 1990). Other studies involving a stereoscopic video system for teleoperation have provided evidence that tasks can be learned more

quickly with less error when binocular depth is present (Drascic, 1991). In an augmented reality application with experienced users, estimations of size using a virtual tape measure produced slight overestimation under stereo viewing at near distances (Drascic & Milgram, 1996; Milgram & Drascic, 1997). While these studies clearly show the efficacy of stereo viewing in near field situations, these experiments did not focus on how stereo viewing affects performance at farther distances. Moreover, these experiments also did not examine how absolute distance is perceived under stereo viewing conditions.

When visually directed action tasks are conducted in virtual environments, the outcome differs from similar real-world studies. Work involving immersive virtual environments has shown that judged distances are underestimated relative to the modeled geometry. In other words, people act upon the spaces as if the spaces were smaller than intended. Previous experiments used HMD technology and focused on 3D environments of hallways or lobby-sized indoor spaces with targets out to about 20 m (Durgin, Fox, Lewis, & Walley, 2002; Lampton, McDonald, Singer, & Bliss, 1995; Knapp, 1999; Loomis & Knapp, 2003; Witmer & Sadowski, 1998; Witmer & Kline, 1998; Sahn, Creem-Regehr, Thompson, & Willemsen, 2005). One common explanation for the underestimation is the relatively small field of view in most HMDs, but recent studies suggest this is not the case for visually directed tasks in action space (Knapp & Loomis, 2004), provided that participants are able to look around the environment (Wu et al., 2004; Creem-Regehr et al., 2005). A small field of view has been shown to degrade performance in search and walking tasks, but these studies did not involve absolute egocentric distance perception (Arthur, 2000). Another explanation for the compression is the lack of realism and graphics quality used in previous studies. However, it has been found that graphics quality is not the main source of compression (Thompson et al., 2004; Willemsen & Gooch, 2002).

The difficulties with accurate presentation of binocular stereo stimuli in an HMD (Wann et al., 1995) have led us to speculate that this may be the cause of underestimations of absolute distance. While binocular stereo

does not directly provide information about absolute distance beyond a few meters, it does provide such information at closer distances. One hypothesis is that depth perception of nearby locations obtained from binocular stereo is combined with relative distance information to farther points to scale environmental space. If this hypothesis is true, then we can predict that removing binocular stereo information should change perception of longer distances. Indeed, the accuracy of such distance judgments might increase when conflicting stereo information is removed. Accuracy could also decrease in real-world conditions when only monocular viewing is allowed. The experiments described below test this hypothesis.

### 3 Experiment: Comparison of Stereo Viewing Conditions

In this experiment, we investigated the effect that stereo viewing has on absolute, egocentric distance judgments. The motivation for these experiments is the possibility that the compression of virtual space reported in previous work can be attributed to problems with stereo viewing in HMDs. If the compression is related to stereo viewing, removing, or minimizing, then any stereo-related conflicts might produce results in which the virtual world appears less compressed.

#### 3.1 Method

**3.1.1 Participants.** Seventy-four subjects (36 females, 38 males), all between the ages of 18 and 35, were drawn from the University of Utah community to participate in these experiments. Participants either had normal, or corrected to normal vision, and were tested for stereo fusion with a stereogram test. Subjects were given compensation for the participation either in the form of a psychology class experiment credit or through a payment of ten dollars.

**3.1.2 Materials.** The equipment used in these experiments consisted of an nVision Datavisor HiRes HMD full color display with interlaced  $1280 \times 1024$



**Figure 1.** Restricted viewing collar in the real and virtual environment setups.

resolution, and a  $52^\circ$  diagonal field of view. The angular resolution of the HMD was on the order of 2 arc minutes per pixel. The display was configured with 100% stereo overlap between the two eyes. The nVision HMD used CRT technology, which avoids a number of visual artifacts found in LCD-based displays that detract from visual realism. The virtual model was rendered on an SGI Onyx2 R12000 with two IR2 rendering pipelines. In the conditions in which stereo vision was required, one rendering pipeline was used for each eye. The virtual environment conditions ran at no less than 30 frames per second. The triangle count in this model was approximately 740 triangles utilizing five texture files. Our software used OpenGL and Sense8's World-Toolkit libraries to load a VRML model created in Alias|Wavefront's Maya Complete. During the portion of the experiment conducted in the real world, the participants' positions and the target locations were recorded by hand with tape measures. In the portion of the experiment in which participants experienced the virtual environment, positions and orientations were recorded using an Intersense IS600-Mark2 tracker. In the computer generated conditions, participants' head orientation was tracked, but translations did not update the rendering of the scene. The IS600-Mark2 tracker updates at 180 Hz and has an angular resolution of  $0.10^\circ$  for orientation tracking.

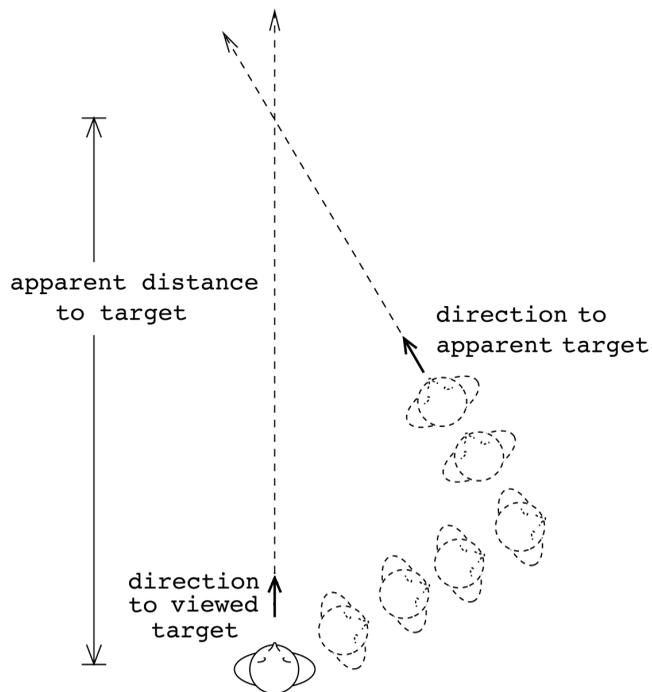
Participants also wore a neck collar in both real and virtual environments. The collar was designed to block a person's view of the ground near their feet radially out to approximately 1.5 m. Figure 1 shows a picture of the

collar in the real and virtual conditions. The collar works by providing a visual occluder in the real world and by acting as a physical barrier in the virtual world that stops a person from bending their neck down to see the ground near their feet. Participants in our studies were told to stop bending their neck down once they felt their chin touch the collar.

The collar was used to avoid potential problems associated with the absence of a virtual body representation or the presence of an unrealistic avatar when looking down. Research has been done to understand the effect of different virtual body representations on spatial awareness, specifically in search and replace tasks, but these studies did not find conclusive evidence that avatar representation produced more accurate results (Draper, 1995). Previous work has showed no effect of the collar on accuracy of directly walking without vision to targets in the real world (Creem-Regehr et al., 2005).

**3.1.3 Stimuli and Design.** We tested the effect of different stereo viewing conditions on judging absolute egocentric distances in both real and virtual environments using a visually directed, triangulated walking task. We utilized a between subjects design with each subject participating in only one viewing condition and environment. The triangulated walking task was chosen for these experiments because it allows us to include target distances outside of the tracked, physical lab space and has been shown to be accurate in real-world studies (Fukushima et al., 1997). Judged distances in previous virtual environment triangulated walking studies have been about 50% of the intended distance (Thompson et al., 2004; Knapp, 1999). Figure 2 illustrates the triangulated walking task used in this experiment.

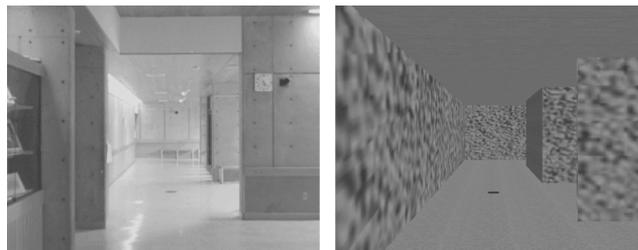
Six conditions were investigated to understand how the presentation of stereo in an HMD affects judged distance. Subjects participated in one of the following conditions: (1) real world, full-cue viewing, (2) real world, with monocular viewing, (3) virtual environment, binocular viewing with fixed IPD of 6.5 cm, (4) virtual environment, binocular viewing with measured IPD, (5) virtual environment, bi-ocular viewing, or (6) virtual environment, monocular viewing. The real world condition of the experiment was conducted in a



**Figure 2.** Visually guided, triangulated walking task.

moderately sized lobby area in a campus building. The computer rendered version of this environment was modeled to provide a replication of the basic geometric properties of the space, matching the size and overall feel of the lobby. The lack of realism in the model did not pose a problem for the current experiments as graphics quality has been shown to not be the main source of absolute, egocentric distance underestimation (Thompson et al., 2004). Figure 3 shows a view of the real world and virtual spaces facing the target.

For near distances, research has provided evidence that correctly modeling eye separation or IPD when generating stereo imagery in head-tracked applications, especially when the display is stationary, is important and must be done carefully to reduce geometric artifacts in the displayed scene (Wartell, Hodges, & Ribarsky, 2002). Additionally, matching the parameters used to render stereoscopic images with the actual configuration and precise layout of an HMD's optical display can be very difficult, resulting in some geometry distortion (Robinett & Rolland, 1992). However, out beyond



**Figure 3.** Real (left) and virtual (right) environments used in experiments.

personal space, it is unclear what effect inaccuracies in IPD have on distance judgments. Conditions (3) and (4) were used to test the effect of IPD on action space distance judgments. In the binocular viewing conditions, stereo images were generated using either a fixed IPD of 6.5 cm, or the participant's measured IPD. The IPD was measured as the distance between monocularly projected pupil locations on a mirror. Participants were placed in front of a mirror and asked to mark the location of their pupils on the mirror one eye at a time. Subjects' heads were kept still during the procedure. To accurately locate the center of the pupil, subjects closed the eye not being marked and placed a dot on the mirror where the open pupil projected. In the measured IPD condition, the mean measured IPD was 6.12 cm, with a range from 5.2 cm to 7.0 cm. In the fixed IPD condition, the mean participant IPD was 6.19 cm, with a range from 5.1 cm to 7.7 cm.

Two real world conditions (full-cue binocular and monocular viewing) were used to verify the accuracy of the triangulation task as a response measure for judging distances, and to understand how real world monocular viewing of targets in action space affects distance judgments. If stereo viewing is a necessary component for accurate triangulated walking, we might expect to find impaired performance with monocular viewing.

Monocular viewing in an HMD removes, or at least minimizes, the accommodation-convergence mismatch. In the event that this mismatch results in an incorrect scaling of the virtual space, monocular viewing may produce more accurate distance judgments.

For both real world and virtual world monocular viewing conditions, participants viewed the world with their dominant eye. Eye dominance was established by using a piece of black foam-core board with a hole cut out of its center. Participants were told to hold the board at arms length and center an object that was located down the hall in the hole using both eyes. Participants then closed their left eye and stated whether or not they were able to see the object. This process was repeated with the right eye. The eye able to view the object down the hall was considered the dominant eye. In both real and virtual monocular conditions, participants wore an eye patch over their nondominant eye.

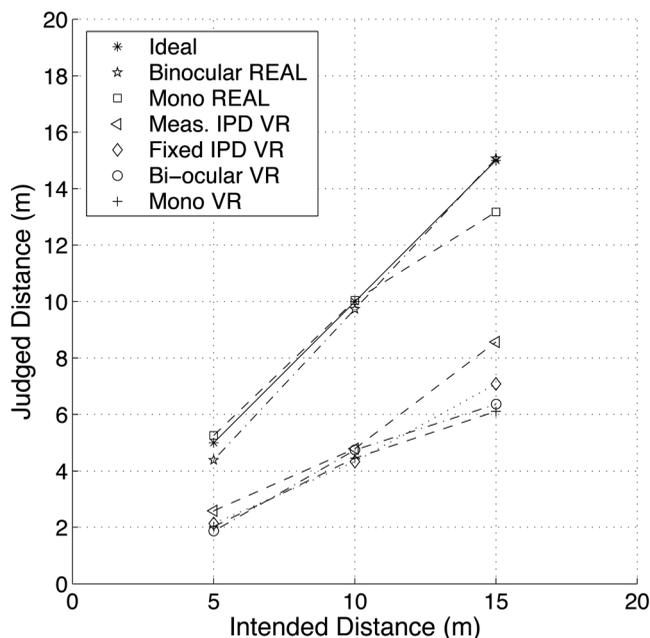
Bi-ocular viewing displays the same image to both eyes, resulting in zero binocular disparity. For the bi-ocular viewing condition, left and right eye images were rendered with an IPD of zero resulting in the nodal point being located directly between the eyes. It was unclear how distance judgments would be affected by this manipulation. One result of bi-ocular viewing in a HMD is that the convergence angle determined by zero binocular disparity may be inconsistent with the actual accommodation of the HMD. Because convergence and accommodation are yoked together in the visual system, it is not entirely clear how these two cues would relate under bi-ocular viewing.

**3.1.4 Procedure.** All participants were first provided with a written description of the experiment task. After reading the instructions, an experimenter presented an equivalent verbal description and demonstration of the task. Participants were not allowed to practice the task. The target used in the real world experiments was a red disk constructed from foam-core board approximately 37 cm in diameter. It provided no familiar size cues and participants were not allowed to see the target prior to the first experiment trial. The target used in the virtual conditions was modeled to resemble the physical target. Participants were informed that their job was to build up a good image, or mental representation, of the target and the local surroundings. The term *good image* was explained to be a clear mental impression of the space. Specifically, when participants closed their eyes, they would still be able to picture the

environment, but most importantly, the target. Participants were allowed as much time as they needed to view the environment and build up their mental representation before they started walking.

Once participants felt confident they had a clear mental image of the space and target, they were instructed to turn away from the target by approximately 60–70° to their right. After turning, participants looked back at the target to verify that the image of the space was still strong and clear. Once participants believed they had a good image of the environment, they informed the experimenters they were ready to walk. Then, either the HMD screen was blanked (HMD), or the participant pulled a blindfold down over their eyes (real world). In either case, participants were also instructed to close their eyes and keep them closed to help focus on their mental representation of the environment. Next, participants walked purposefully and decisively away from the target. At a point along their walking path (approximately 2.5 m from the starting position), an experimenter instructed the participant to turn by saying the word *turn*. This indicated to the participant to turn and face the target and to stop walking. Participants were told that they could walk a few steps in the direction of the target if they felt it gave them better accuracy, but should stop after a couple of steps at most. The experimenter then directed participants to take two additional steps toward the target. Participants understood that they would never actually reach the target.

Even though absolute motion parallax has been shown to be only a weak cue for absolute distance judgments (Beall & Loomis, 1995), we attempted to reduce any effects resulting from motion parallax by instructing participants to not move their body by bending at the waist, side-stepping, or swaying while forming a mental representation of the environment. Participants were allowed to rotate their head about their neck in a left to right, or up and down manner to ensure a complete view of the space. Constraining a participant's head movement in this way minimized, but did not eliminate, motion parallax. With normal head rotation, small translations do occur and thus, the rotations produce a small amount of motion parallax. Only under pure rotation about an axis is motion parallax completely removed.



**Figure 4.** Comparison of all viewing conditions.

Prior to each experiment, participants were given approximately 5 min of practice walking without vision in which the experimenter verbally instructed participants to start, stop, and turn. This process familiarized the participant with blind walking, but also served as a trust building exercise between the participant and the experimenter. No feedback was provided during any phase of the experiment, and to reduce any auditory cues to distance, participants wore sound-masking headphones that mixed a masking noise with input from a wireless microphone worn by the experimenter. Three training trials were conducted for each condition, followed by three trials at each of the three distances. The order in which the distances were presented was randomized for each participant.

### 3.2 Results

As can be seen in Figure 4, we replicated the large difference between judgments made in real versus virtual environments seen in previous research. Whereas judgments were near accurate in the real world, they

showed a large systematic underestimation of approximately 45% in all of the virtual environment conditions. There was no obvious effect of the stereo viewing manipulations. Table 1 displays the average judged distances from all conditions along with standard error of the mean ( $\pm 1$  SEM). An artifact of using a triangulated walking task as a response measure for perceived distance is that distance judgments are biased by target distances. Small differences in the direction to the apparent target for far targets changes perceived distance more than small differences at near targets. An arctangent transform (Thompson et al., 2004) was applied to the data to reduce this effect. All statistical analyses were calculated in the transform space.

A 6 (environment)  $\times$  3 (distance) repeated measures ANOVA with distance as a within-subject variable and environment as a between subject variable was computed on the transformed averages of the distance judgments. The ANOVA indicated an effect of environment ( $F(5, 68) = 11.67, p < .001$ ). Planned contrasts showed that the monocular and binocular real world conditions were not different from each other ( $p = .837$ ); both showed near perfect performance and were different from all of the virtual conditions ( $p < .01$  for all contrasts). A calculation of effect sizes confirmed these effects as the difference between the real world conditions was very small ( $d = 0.09$ ) whereas comparisons of both real world conditions to all VE conditions showed large differences ( $d$  ranged from 1.45 to 2.45). The planned contrasts revealed that there were no significant differences among the virtual conditions (mono vs. bi-ocular,  $p < .90$ ; bi-ocular vs. fixed IPD,  $p < .83$ ; fixed IPD vs. measured IPD,  $p < .37$ ). Effect sizes for comparisons between mono VR, bi-ocular VR, and fixed IPD VR were small ( $d$  ranged from 0.04 to 0.16) whereas measured IPD VR, showing slightly improved performance at 15 m, led to medium-sized differences when compared with the other VE conditions ( $d$  ranged from 0.35 to 0.48). As would be expected, there was also a main effect of distance,  $F(2, 136) = 152.44, p < .01$ , and no interaction between environment and distance; judgments increased as actual distance increased for all environments.

**Table 1.** Results from Each Condition—All Values Are in Meters

Targets	5.0	10.0	15.0
(a) Binocular viewing, full-cue, real environment			
Mean	4.38	9.74	15.07
−1 SEM	0.30	0.82	1.93
+1 SEM	0.31	0.93	2.44
(b) Monocular viewing, full-cue, real environment			
Mean	5.26	10.04	13.17
−1 SEM	0.71	0.97	1.75
+1 SEM	0.79	1.12	2.21
(c) Binocular viewing with measured IPD, virtual environment			
Mean	2.58	4.79	8.57
−1 SEM	0.42	0.69	1.36
+1 SEM	0.43	0.76	1.67
(d) Binocular viewing with fixed IPD, virtual environment			
Mean	2.14	4.33	7.09
−1 SEM	0.19	0.45	1.10
+1 SEM	0.20	0.48	1.29
(e) Bi-ocular viewing, virtual environment			
Mean	1.86	4.74	6.36
−1 SEM	0.22	0.80	1.25
+1 SEM	0.22	0.89	1.51
(f) Monocular viewing, virtual environment			
Mean	2.02	4.45	6.11
−1 SEM	0.55	0.62	0.94
+1 SEM	0.58	0.67	1.08

#### 4 Conclusion

Matching space perception in real and virtual environments is important, particularly in simulation, education, and training applications. Understanding why absolute egocentric distances are misperceived in current HMD systems should lead to more applicable and useful virtual reality technology.

We hypothesized that performance in blind walking might differ among stereo versus monocular or bi-ocular viewing conditions. However, the results of our investigations show that this hypothesis was not sup-

ported and suggest that inaccuracies in stereo viewing conditions in HMDs are not the likely source of compressed distance judgments within action space. Minimizing accommodation-convergence cue conflicts in the monocular and bi-ocular viewing conditions did not affect the accuracy of distance judgments. Using measured IPD for rendering the binocular views of each participant did not significantly improve overall performance as compared to using a fixed IPD of 6.5 cm. Furthermore, performance under monocular viewing in the real world remained accurate. It is difficult to make finite conclusions about the presence or absence of stereo

viewing effects from a null finding. There remains the possibility that differences do exist but that our measure was not sensitive enough to detect them. However, both traditional statistical comparisons of means and calculation of effect sizes support the conclusion that the underestimation found in our study is not a result of the unnatural stereo viewing conditions commonly found with HMDs and visually immersive applications. It is still not clear why actions in virtual spaces indicate the spaces are smaller than intended. Additional investigation should focus on other factors as a source of the compression.

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## References

- Arthur, K. W. (2000). *Effects of field of view on performance with head mounted displays*. Unpublished doctoral dissertation, Department of Computer Science, University of North Carolina, Chapel Hill.
- Beall, A. C., & Loomis, J. M. (1995). Absolute motion parallax weakly determines visual scale in real and virtual environments. *Proceedings of SPIE*, 2411, 288–297.
- Bingham, G., Bradley, A., Bailey, M., & Vinner, R. (2001). Accommodation, occlusion and disparity matching are used to guide reaching: A comparison of actual versus virtual environments. *Journal of Experimental Psychology: Human Perception and Performance*, 27(6), 1314–1344.
- Creem-Regehr, S. H., Willemsen, P., Gooch, A. A., & Thompson, W. B. (2005). The influence of restricted viewing conditions on egocentric distance perception: Implications for real and virtual indoor environments. *Perception*, 34(1), 191–204.
- Cutting, J. E., & Vishton, P. M. (1995). Perceiving layout and knowing distances: The integration, relative potency, and contextual use of different information about depth. In W. Epstein & S. Rogers (Eds.), *Perception of space and motion* (pp. 69–117). San Diego, CA: Academic Press.
- Doshier, B. A., Sperling, G., & Wurst, S. A. (1986). Tradeoffs between stereopsis and proximity luminance covariance as determinants of perceived 3D structure. *Vision Research*, 26(6), 973–990.
- Draper, M. (1995). *Exploring the influence of virtual bodies on spatial awareness*. Unpublished master's thesis, College of Engineering, University of Washington.
- Drascic, D. (1991). Skill acquisition and task performance in teleoperation using monoscopic and stereoscopic video remote viewing. In *Proceedings of the Human Factors Society's 35th Annual Meeting*, 1367–1371.
- Drascic, D., & Milgram, P. (1996). Perceptual issues in augmented reality. *SPIE, Stereoscopic Displays and Virtual Reality Systems III*, 2653, 123–134.
- Durgin, F., Fox, L., Lewis, J., & Walley, K. (2002). Perceptuomotor adaptation: More than meets the eye. Paper presented at the Annual Meeting of the Psychonomic Society, 7, 103 (Abstract).
- Ellis, S. R., & Menges, B. M. (1997). Judgments of the distance to nearby virtual objects: Interaction of viewing conditions and accommodative demand. *Presence: Teleoperators and Virtual Environments*, 6(4), 452–460.
- Foley, J. M. (1980). Binocular distance perception. *Psychological Review*, 87(5), 411–434.
- Fukushima, S. S., Da Silva, J. A., & Loomis, J. M. (1997). Visual perception of egocentric distance as assessed by triangulation. *Journal of Experimental Psychology: Human Perception and Performance*, 23(1), 86–100.
- Gogel, W. C. (1961). Convergence as a cue to the perceived distance of objects in a binocular configuration. *Journal of Psychology*, 52, 303–315.
- Hu, H., Gooch, A. A., Creem-Regehr, S., & Thompson, W. B. (2002). Visual cues for perceiving distances from objects to surfaces. *Presence: Teleoperators and Virtual Environments*, 11(6), 652–664.
- Kim, W. S., Ellis, S. R., Tyler, M. E., Hannaford, B., & Stark, L. (1987). Quantitative evaluation of perspective and stereoscopic displays in three-axis manual tracking tasks. *SMC-17*, 61–71.
- Knapp, J. M. (1999). *The visual perception of egocentric distance in virtual environments*. Unpublished doctoral dissertation, University of California at Santa Barbara.
- Knapp, J. M., & Loomis, J. M. (2004). Limited field of view of head-mounted displays is not the cause of distance un-

- derestimation in virtual environments. *Presence: Teleoperators and Virtual Environments*, 13(5), 572–577.
- Lampton, D. R., McDonald, D. P., Singer, M., & Bliss, J. P. (1995). Distance estimation in virtual environments. In *Proceedings of the Human Factors and Ergonomics Society*, 1268–1272.
- Loomis, J. M., Da Silva, J. A., Fujita, N., & Fukusima, S. S. (1992). Visual space perception and visually directed action. *Journal of Experimental Psychology: Human Perception and Performance*, 18, 906–921.
- Loomis, J. M., & Knapp, J. M. (2003). Visual perception of egocentric distance in real and virtual environments. In L. J. Hettinger & M. W. Haas (Eds.), *Virtual and adaptive environments* (pp. 21–46). Mahwah, NJ: Erlbaum.
- Milgram, P., & Drascic, D. (1997). Perceptual effects in aligning virtual and real objects in augmented reality displays. In *Proceedings of the Human Factors and Ergonomics Society 41st Annual Meeting*.
- Philbeck, J. W., Loomis, J. M., & Beall, A. C. (1997). Visually perceived location is an invariant in the control of action. *Perception and Psychophysics*, 59(4), 601–612.
- Reinhart, W. F., Beaton, R. J., & Snyder, H. L. (1990). Depth cueing for visual search and cursor positioning. In *Proceedings of SPIE, Stereoscopic Displays and Applications*, 1256, 12–21.
- Rieser, J. J., Ashmead, D. H., Taylor, C. R., & Youngquist, G. A. (1990). Visual perception and the guidance of locomotion without vision to previously seen targets. *Perception*, 19, 675–689.
- Robinett, W., & Rolland, J. P. (1992). A computational model for the stereoscopic optics of a head-mounted display. *Presence: Teleoperators and Virtual Environments*, 1(1), 45–62.
- Sahm, C. S., Creem-Regehr, S. H., Thompson, W. B., & Willemsen, P. (2005). Throwing versus walking as indicators of distance perception in similar real and virtual environments. *ACM Transactions on Applied Perception*, 2(1), 35–45.
- Surdick, R. T., Davis, E. T., King, R. A., & Hodges, L. F. (1997). The perception of distance in simulated visual displays: A comparison of the effectiveness and accuracy of multiple depth cues across viewing distances. *Presence: Teleoperators and Virtual Environments*, 6(5), 513–531.
- Thompson, W. B., Willemsen, P., Gooch, A. A., Creem-Regehr, S. H., Loomis, J. M., & Beall, A. C. (2004). Does the quality of the computer graphics matter when judging distances in visually immersive environments? *Presence: Teleoperators and Virtual Environments*, 13(5), 560–571.
- Thomson, J. A. (1983). Is continuous visual monitoring necessary in visually guided locomotion? *Journal of Experimental Psychology: Human Perception and Performance*, 9(3), 427–443.
- Wann, J. P., Rushton, S., & Mon-Williams, M. (1995). Natural problems for stereoscopic depth perception in virtual environments. *Vision Research*, 35(19), 2731–2736.
- Wartell, Z., Hodges, L. F., & Ribarsky, W. (2002). A geometric comparison of algorithms for fusion control in stereoscopic HTDS. *IEEE Transactions on Visualization and Computer Graphics*, 8(2), 129–143.
- Willemsen, P., Colton, M., Creem-Regehr, S., & Thompson, W. (2004). The effects of head-mounted display mechanics on distance judgments in virtual environments. In *ACM SIGGRAPH Symposium on Applied Perception in Graphics and Visualization*, 35–38.
- Willemsen, P., & Gooch, A. (2002). Perceived egocentric distances in real, image-based, and traditional virtual environments. In *Proceedings of IEEE Virtual Reality*, 275–276.
- Witmer, B. G., & Kline, P. B. (1998). Judging perceived and traversed distance in virtual environments. *Presence: Teleoperators and Virtual Environments*, 7(2), 144–167.
- Witmer, B. G., & Sadowski, W. J., Jr. (1998). Nonvisually guided locomotion to a previously viewed target in real and virtual environments. *Human Factors*, 40, 478–488.
- Wu, B., Ooi, T. L., & He, Z. J. (2004). Perceiving distance accurately by a directional process of integrating ground information. *Nature*, 428, 73–77.