# 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-pupilary distances, as well as bi-ocular and monocular viewing of graphics, on absolute distance judgments. Our results indicate 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.

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## Abstract

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## 1. Introduction

Subjective experience and empirical research suggest that there are differences in human perception between 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 perceive the distances accurately. The cause of the compression is unknown. Our research investigates whether the compression of space in the virtual environment stems from differences in viewing conditions between real and HMD environments. Specifically, do inaccuracies in stereo viewing in HMDs affect absolute, egocentric distance judgments. Our data suggests that for targets on the ground placed out to 15m, inaccuracies in stereo viewing conditions inherent in HMDs are not the main source of compression.

Perception of absolute depth in the real world depends on several visual cues. Most visual cues provide only relative or ordinal depth information, while a select few can provide scaling information necessary to recover absolute depth. Absolute depth cues include familiar size, motion parallax, angular declination 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. The amount to which these cues influence perception varies with distance. For space perception, Cutting and Vishton [4] have found it useful to divide the environment around an observer into distance classifications: personal space (within arm's reach), action space (2-30 meters), and vista space (beyond 30 meters). Within action space, accommodation, convergence, and motion parallax are considered to be weak cues for absolute distance [2, 10] as their individual effects tend to diminish out past 2 meters. However, absolute depth beyond 2 meters can be recovered from binocular disparity by using convergence as a scaling factor [8]. There is also evidence that near distance ground surface cues are important for perceiving farther distances [29].

In HMD environments, technological characteristics make presentation of precise visual cues problematic. In particular, presenting stereo information accurately in HMDs is difficult [24]. 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 [10]. Binocular disparity is susceptible to distortions caused by the optics used in HMDs. While inter-pupilary distance (IPD) is important for personal space viewing, it is difficult to match exactly in most HMDs [20]. Due to the lack of precise control over image position and accommodation, IPD can only roughly be controlled. HMDs allow user adjustment of IPD and position on the head. Some also allow user adjustment of focus. Almost always, calibrated infor-

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mation about these adjustments cannot be obtained.

This paper investigates the hypothesis that the spatial compression observed in previous absolute egocentric distance studies using HMDs is a result of unnatural viewing conditions and addresses the question of whether the source of distance misperception is a result of inappropriate absolute scaling caused by stereo imagery in HMDs. While stereo has little direct influence on absolute distance to specific locations beyond personal space, it is possible that stereo may help scale the space and thus indirectly contribute to absolute distance perception. If this is the case, then inaccuracies in stereo perception in an HMD might well result in misperception of absolute distances even in action space.

In our study, we varied the presentation of stereo information in a 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 absolute distance in the real world. Absolute distance judgments were obtained using a visually directed action in which participants first viewed the target and then walked without vision toward the target. Our results strongly suggest that within action space, absolute egocentric distance judgments are not being compressed as a result of conflicting stereo cues in HMDs since all virtual conditions involving stereo manipulations (monocular, bi-ocular, and differing IPD) produced amounts of compression similar to previous reports.

## 2. Related Work

Human perception research from the psychology and vision science communities is becoming increasingly useful to researchers in computer graphics and virtual environments. Our work combines efforts from these areas and virtual environment practitioners 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[19, 23]. In particular, this research has shown that visually guided actions such as blind walking to previously viewed targets are good response measures for how physical space maps to perceived visual space [9, 12, 16, 18]. 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. Results from these studies, conducted in real world hallways and outdoor spaces under full cue conditions, show that people are accurate at judging distances to targets resting on the ground out to about 25 meters.

Other research efforts have investigated the effectiveness of different cues for absolute distance perception. Accommodation and convergence are absolute egocentric cues, but individually, do not have much direct effect beyond personal space [4]. Similarly, beyond personal space, absolute motion parallax has been found to be a weak cue for absolute distance [2].

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. Thus, 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 meters [6, 13, 15, 17, 27, 28]. 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 [14], provided that participants are able to look around the environment [3]. 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 [1]. 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 [22, 26].

While stereo in visually immersive applications is known to be effective for interaction within personal space [7, 11, 21], it is unclear if inaccuracies in stereo viewing in HMDs are indirectly affecting the scaling of the virtual space resulting in underestimations of absolute distance. This paper investigates the role that stereo vision in HMDs has on perception of absolute egocentric distance out to 15 meters and addresses the question of whether problems with presenting stereo accurately in HMDs is the source of compression.

## 3. Experiment Information

We used a visually directed, triangulated walking task as a response measure for judged distance to targets on the ground at 5, 10, and 15 meters. In this task, participants first viewed the target, turned to the side, and then walked without visual feedback in the direction they were facing. After traveling a short distance, each participant was verbally instructed to turn to face the target and walk a few steps in its direction, still without visual feedback. Figure 1 illustrates the triangulated walking task. The use of triangulated walking was chosen for these experiments because it allows us to include target distances outside of our tracked, physical space and has been shown to be accurate in real-world studies [9]. Judged distances in previous virtual environment triangulated walking studies has been about 50% of the intended distance [13, 22].

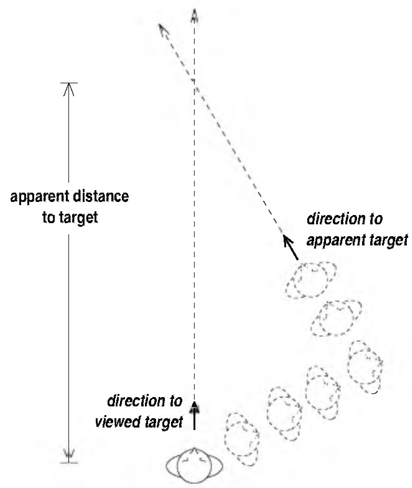


Figure 1: Visually guided, triangulated walking task.

## 3.1. Methodology

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 37cm 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.

Even though absolute motion parallax has been shown to be only a weak cue for absolute distance judgments [2], we attempted to reduce any artifacts 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.

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 degrees 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, or the participant pulled a blindfold down over their eyes. 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 meters 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.

Figure 2: Restricted viewing collar in the real and virtual environment setups.

Prior to each experiment, participants were given approximately 5 minutes 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 and the order in which the distances were presented was randomized for each participant.

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 meters. Figure 2 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 [5]. An experiment analyzing the effect of wearing the collar on absolute, egocentric distance perception in the real world is presented in Section 4.3. In this experiment, wearing the collar did not affect perception of absolute distances.

## 3.2. Equipment and Software

The equipment used in these experiments consisted of a nVision Datavisor HiRes HMD full color display with interlaced 1280x1024 resolution, and a 52 degree diagonal field of view. The angular resolution of the HMD is on the order of 2 arc minutes per pixel. The display was configured with 100% stereo overlap between the two eyes. The nVision HMD uses 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 5 texture files. Our software uses OpenGL and Sense8's WorldToolKit 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 were recorded using an IS600-Mark2 Intersense tracker. In the computer generated conditions, participants were afforded head rotation through the tracking device, but translations did not update the rendering of the scene.

## 4. Seeing the World with Unnatural Eyes

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

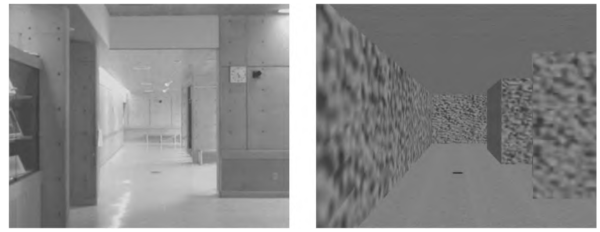

Figure 3: Real (left) and virtual (right) environments used in experiments.

### 4.1. Experiment: *Monocular, Bi-ocular, Binocular Comparison*

We tested the effect of different stereo viewing conditions on judging absolute egocentric distances in both real and virtual environments. We utilized a between subjects design with each subject participating in only one viewing condition and environment. A total of 74 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.

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 6.5cm, (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 moderately sized lobby area in a campus building. The computer rendered version of this environment was modeled to match the general feel of the space and it's dimensions. Figure 3 shows a view of the real-world and virtual spaces facing the target.

Two real world conditions (full-cue 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.

Monocular viewing in an HMD is interesting because it removes, or at least minimizes, the accommodation-convergence mismatch. In the event that this mismatch is resulting 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 non-dominant eye.

Bi-ocular viewing is interesting because the same image is displayed to both eyes, resulting in zero binocular disparity. It was unclear how distance judgments would be affected by this manipulation. 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.

Research has shown that correctly modeling eye separation or IPD when generating stereo imagery is important and must be done carefully [20, 25]. However, out beyond personal space, it is unclear what effect inaccuracies in IPD have on distance judgments. Two conditions were used to test this effect. In the binocular viewing conditions, stereo images were generated using either a fixed IPD of $6.5cm$, or the participant's measured IPD. 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 $6.12cm$, with a range of $[5.2cm, 7.0cm]$. In the fixed IPD condition, mean participant IPD was $6.19cm$, with a range of $[5.1cm, 7.7cm]$.

## 4.2. Results

Figures 4–9 show the average judged distances from all conditions. Error bars represent $\pm 1$ SEM and are not necessarily symmetric. 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 was applied to the data to reduce this effect. Analysis of means, error estimates, and measures of statistical significance were calculated in the transform space. Figure 10 compares all results together.

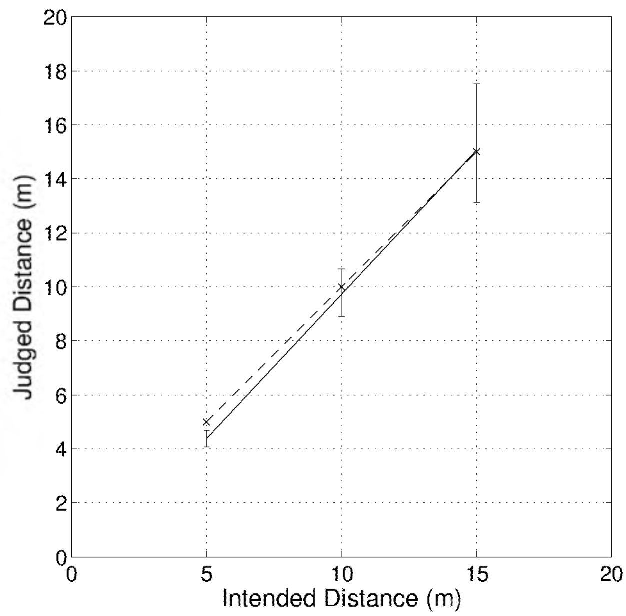


Figure 4: Full-cue, Real Environment Condition. Error bars represent $\pm 1$ SEM. The dashed line represents ideal performance.

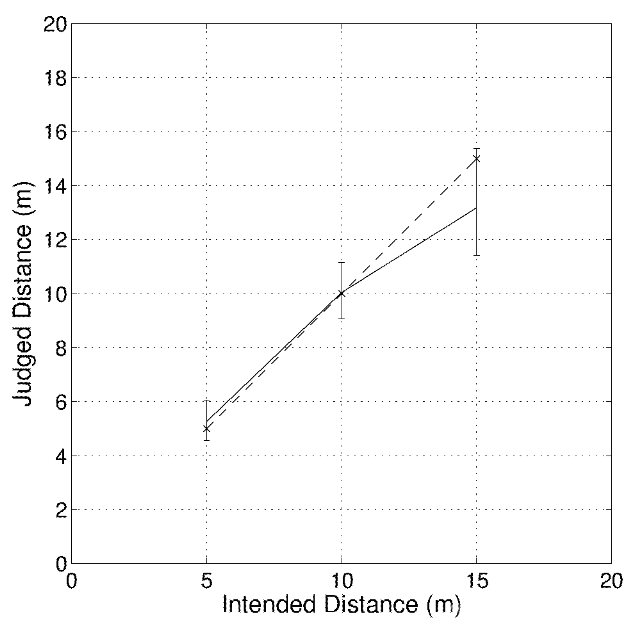


Figure 5: Monocular, Real Environment Condition. Error bars represent $\pm 1$ SEM. The dashed line represents ideal performance.

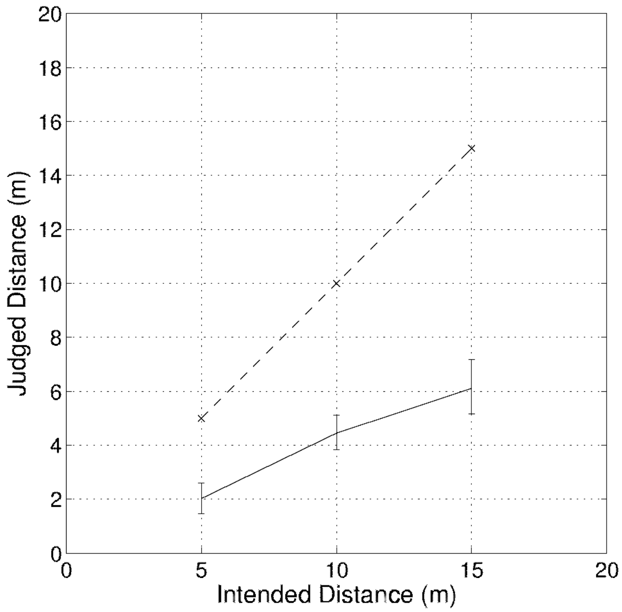


Figure 6: Monocular, Virtual Environment Condition. Error bars represent $\pm 1$ SEM. The dashed line represents ideal performance.

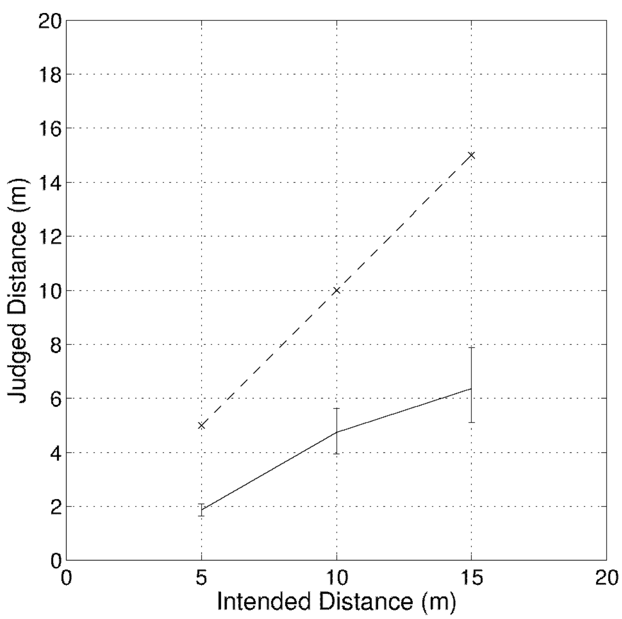


Figure 7: Bi-ocular, Virtual Environment Condition. Error bars represent $\pm 1$ SEM. The dashed line represents ideal performance.

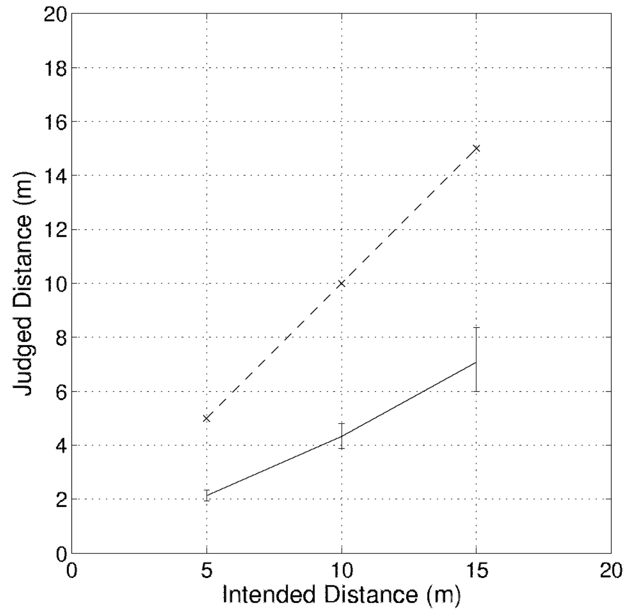


Figure 8: Fixed IPD of 6.5cm, Binocular, Virtual Environment Condition. Error bars represent $\pm 1$ SEM. The dashed line represents ideal performance.

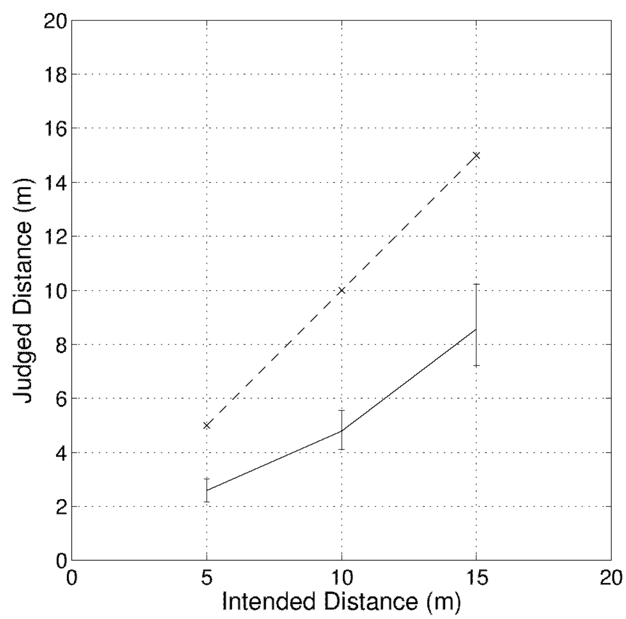


Figure 9: Measured IPD, Binocular, Virtual Environment Condition. Error bars represent $\pm 1$ SEM. The dashed line represents ideal performance.

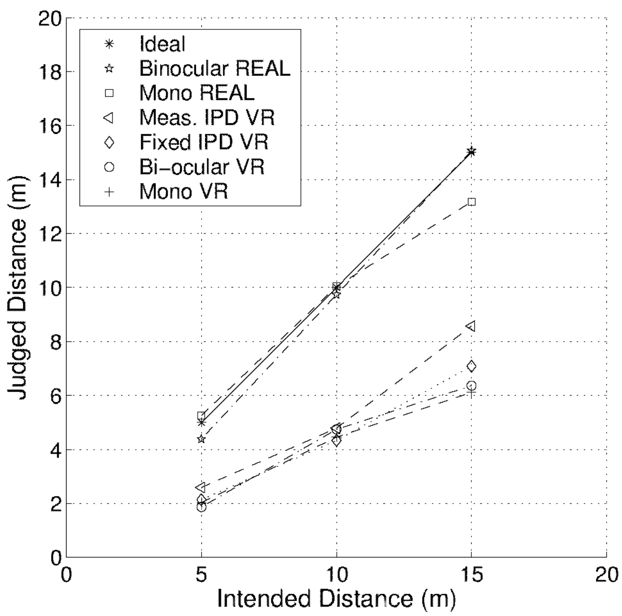


Figure 10: Comparison of all viewing conditions.

A 6 (environment) x 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 ($F(5, 68) = 11.67, p < 0.001$). Scheffe post hoc tests showed that the monocular and binocular real-world conditions were not different from each other ($p = 1.0$); both showed near perfect performance and were different from all of the virtual conditions ($p < .05$ for all comparisons). There were no significant differences between any of the virtual conditions ($p > .9$ for all comparisons); all showed a similar judged distance of approximately $45\%$, which is similar to previous results using triangulated walking tasks.

## 4.3. Effect of Collar

This experiment examined the effects of wearing the collar on absolute distance judgments in the real world. The experiment used a 2 (collar) x 3 (distance) between-subjects experimental design in which the presence of the collar was varied between subjects. With the exception of the collar manipulation, the experiment followed the methodology described in Section 3.1. A total of 25 subjects (13 females, 12 males) were drawn from the University of Utah community and all were between the ages of 18 and 35. Participants either had normal, or corrected to normal vision and were tested for ability to fuse stereo images with a stereo-gram test.

Table 1 shows the average judged distance, along with SEM values. A 2 (collar) x 3 (distance) repeated measures ANOVA with distance as a within-subject variable and environment as a between-subject variable was performed on the transformed average distance judgments. The analysis indicates no effect of collar on distance judgments, $F(1, 23) = 0.094$, $p > 0.7$. Overall, the analysis verifies that wearing the collar did not alter accurate performance in the real-world.

| | **No Collar** | | | **With Collar** | | |
|---|---|---|---|---|---|---|
| **Targets** | *5.0* | *10.0* | *15.0* | *5.0* | *10.0* | *15.0* |
| **Mean** | 5.25 | 10.1 | 14.1 | 4.38 | 9.74 | 15.1 |
| **SEM Min** | 0.62 | 1.37 | 2.35 | 0.30 | 0.82 | 1.93 |
| **SEM Max** | 0.68 | 1.67 | 3.20 | 0.31 | 0.93 | 2.44 |

Table 1: Real-world collar conditions. All values are in meters.

## 5. 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.

The results of our investigations show that inaccuracies in stereo viewing conditions in HMDs are not the likely source of compressed distance judgments within action space. Eliminating 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 improve overall performance as compared to using a fixed IPD of $6.5cm$. Furthermore, performance under monocular viewing in the real world remained accurate. We can conclude that within action space (2-30m), underestimation of absolute, egocentric distance to targets on the ground plane is not a result of the unnatural stereo viewing conditions commonly found with HMDs and visually immersive applications.

Thus, it is still not clear why actions in virtual spaces indicate the spaces are smaller than intended. Additional investigation needs to focus on other factors as a source of the compression. Perhaps the ergonomics of wearing the HMD or sense of presence are important characteristics that are missing from visually immersive experiences.

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