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Limited Field of View of Head-Mounted Displays Is Not the Cause of Distance Underestimation in Virtual Environments

Abstract

Observers binocularly viewed a target placed in a large open field under two viewing conditions: unrestricted field of view and reduced field of view, as effected using a simulated head-mounted display. Observers indicated the perceived distance of the target, which ranged from 2 to 15 m, using both verbal report and blind walking. For neither response was there a reliable effect of limiting the field of view on the perception of distance. This result indicates that the significant underperception of distance observed in several studies on distance perception in virtual environments is not caused by the limited field of view of the head-mounted display.

1 Introduction

Several studies on distance perception in virtual environments using head-mounted displays (HMDs) have found significant underestimation of egocentric distance, the distance from an observer to a target (Witmer & Kline, 1998; Witmer & Sadowski, 1998; Knapp, 1999; Durgin, Fox, Lewis, & Walley, 2002; Thompson et al., in press). Figure 1 gives such a result (from Loomis & Knapp, 2003, as based on the experimental results of Knapp, 1999). Observers binocularly viewed targets on a simulated ground plane with texture. The HMD used in the experiment was a Virtual Research FS5, which has a 47° horizontal by 36° vertical field of view in each eye, with 100% binocular overlap, and which was run with a spatial resolution of 800 horizontal × 486 vertical. Three methods of indicating perceived distance were used. With verbal report, the observer simply estimated distance to a visual target in terms of familiar distance units, such as feet. The size-based response involved the subject making an estimate of the size of a visual target. The estimates of size were then used to compute perceived distance, according to the perceptual relationship known as size-distance invariance (Loomis & Knapp, 2003). Finally, the motor response involved what has been termed "visually directed action" (Loomis & Knapp, 2003). Typically, an observer views a target and then, with eyes closed, attempts to indicate its perceived and remembered location through some form of locomotor response. Walking directly to the perceived target location with eyes closed (blind walking) is one such response. Another is "triangulation by walking" or "triangulated walking," in which the

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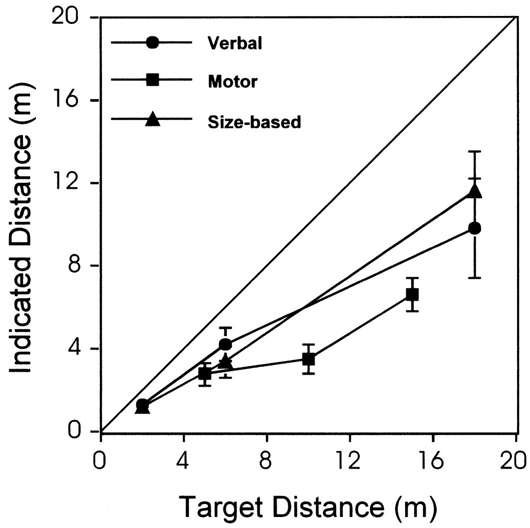

Figure 1. *Comparison of three measures of perceived egocentric distance: verbal report, a locomotor measure derived from triangulation by walking, and a measure derived from the judgment of perceived size. Error bars represent one standard error of the mean. (Figure adapted from Figure 2.7 of Loomis & Knapp, 2003, as based on the experimental results of Knapp, 1999. Reprinted with permission.)*

subject views the target, walks along a straight path oblique to the target direction, and then, at some point, turns and attempts to face or walk toward the target (Fukusima, Loomis, & Da Silva, 1997). The facing or walking direction after the turn is used to estimate the initially perceived target location. The motor response in Figure 1 was obtained using triangulation by walking (Knapp, 1999). It is clear that the three different ways of estimating perceived distance agree in showing that perceived egocentric distance was approximately 50% that of the simulated target distance in a virtual environment involving a flat ground plane with texture and binocular cues. More recently, Thompson et al. found approximately the same degree of underestimation (50%) using triangulation by walking. Durgin et al. and Willemsen and Gooch (2002) obtained less but still significant underestimation using blind walking. In contrast, when these two forms of visually directed action are used in full-cue viewing conditions in a real grassy field, the results indicate linear and accurate perception of distance out to at least 20 m (see Loomis and Knapp, 2003 for a summary of many such studies). Thus, HMD-based virtual environments produce significant underestimation of perceived distance compared to real environments, although Witmer and Sadowski obtained much more accurate perception of distance using a walking response on a treadmill than what is shown in Figure 1. Also, we note that some researchers using augmented reality displays have reported quite accurate distance perception (e.g., Ellis & Menges, 1997), especially for short distances, but in these cases, subjects can use precise relative-distance cues (like binocular disparity and relative-motion parallax) to perceive the virtual targets in relation to features within the full-cue real environments. To elaborate, even if a virtual target in isolation might be misperceived in distance, the availability of binocular disparity between it and targets in a real environment would allow the observer to use disparity matching to precisely localize the virtual target relative to the real targets (Bingham, Bradley, Bailey, & Vinner, 2001); if the real targets are perceived accurately, then so would be the virtual target of equal vergence. In contrast, in fully immersive nonaugmented virtual environments, all of the visual cues for egocentric distance perception must come from the simulated environment.

There are a number of possible reasons that distance is underperceived in HMD-based virtual environments (Kline & Witmer, 1996; Durgin et al., 2002; Loomis & Knapp, 2003; Thompson et al., in press). These include incongruence between simulated and accommodative distance (Bingham et al., 2001), limited field of view (FOV), dynamic range and spatial resolution of the visual display, the fidelity with which environmental cues are graphically rendered, and knowledge on the part of the observer that he or she is in a simulated environment. Thompson et al. examined the fidelity issue by varying the graphical rendering of a virtual environment (from wireframe to photorealistic) while using a high-resolution HMD, and found no effect on distance perception (see Willemsen & Gooch, 2002, for a similar experiment and conclusion). The current study tests the hypothesis that the limited FOV of the typical HMD causes a misperception of distance.

An ideal test of the hypothesis is to compare, in a virtual environment, distance perception with the restricted FOV of the typical HMD and with the unrestricted FOV of human vision. No study quite like this has been reported, but there are several relevant studies of FOV and distance perception. Arthur (2000) studied distance perception, among other abilities, in a virtual environment using HMDs that varied in horizontal FOV from 48° to 176° and observed no effect of FOV on the accuracy of distance perception. However, Arthur's task for measuring distance perception was a bit unconventional—observers continuously viewed the location of the target as they walked past it while traversing a multisegment route, then later recalled the location of the target while standing at the origin of travel, and then walked directly to its remembered location. Kline and Witmer (1996) used a more conventional method—observers viewed targets in a virtual environment from a fixed location and indicated their perceived distances using verbal report. The wide FOV was 140° horizontal × 90° vertical, and the narrow FOV was 60° horizontal × 38.5° vertical. Kline and Witmer found that limiting FOV greatly reduced the ability to discriminate distance, a result they attribute to a reduction or elimination of perspective cues with the narrow FOV. However, in contrast to what is typical of behavior in virtual environments, the head was not free to rotate, a feature of the experiment that undoubtedly made display FOV much more critical. Two other studies have investigated the effect of reducing FOV on the perception of distances (Watt, Bradshaw, & Rushton, 2000; Bingham & Pagano, 1998). Using reaching to targets within arm's reach, these studies found that reducing FOV to a size typical of HMDs produced slight underestimation of reaching distance.

The experiment we report here was performed within a real environment instead of a virtual environment. Because we did not have access to an HMD with a large FOV approaching that of normal vision, we instead conducted our study outdoors with real targets in a large open field and we manipulated the observer's FOV using a device simulating a typical HMD. If it is true that the restricted FOV of typical HMDs is the cause of the large underestimation of distance perception reported in several of the studies mentioned above, similarly restricting FOV in a real environment ought to produce significant underestimation of distance.

2 Method

Ten observers, five male and five female students at the University of California, Santa Barbara, were paid for participation in the study. The experiment took place in a large flat grassy field on the UCSB campus. Trees, buildings, and other objects surrounding the field were visible during the experiment. Observers viewed a red Styrofoam sphere measuring 10 cm in diameter that was presented at 6 distances from the observer's position (2, 3, 6, 10, 12, and 15 m, as measured along the ground.) Because three of these distances (2, 6, and 12 m) were of primary interest, we obtained more responses to each. To minimize learning of the three target locations over the course of the experiment, the other three target distances were interspersed, with lower incidence, as "dummy trials" throughout the experiment.

Two different viewing conditions were employed: unrestricted FOV (roughly 180° horizontal × 120° vertical) and reduced field of view. The latter condition made use of a "simulated HMD," which consisted of a rectangular box made from cardboard and Styrofoam attached to a pair of plastic safety goggles with clear lenses (Figure 2). By design, the field limiting rectangular aperture (14 cm horizontal × 12 cm vertical) was located 15.2 cm in front of the eyes. The FOV of each eye was 47° horizontal × 43° vertical. The combined horizontal FOV for the two eyes was 58° and the region of binocular overlap subtended 36°. These dimensions are just slightly larger than those of the HMD used in obtaining the results in Figure 1, but are typical of many other HMDs (Arthur, 2000).

The interior of the simulated HMD was covered with black felt and light-catching baffles so that the observer's FOV was dark except for the visual field seen through the aperture. Observers wore the lightweight device as they would a diving mask. It was secured to the head using an elastic strap (Figure 2). As with the typical HMD, movements of the head were not im-

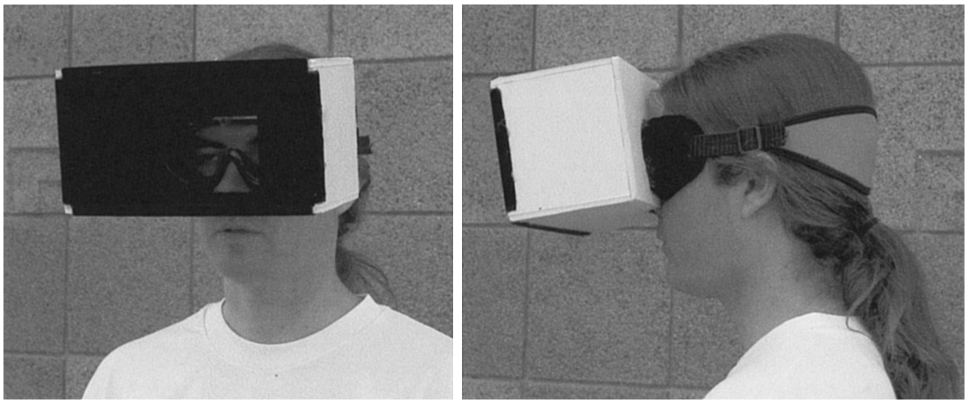

Figure 2. *Two views of the simulated HMD.*

peded in any way by the device. Thus, observers were free to move their heads while estimating the distance of the target. Given that the vertical FOV was quite limited, vertical head movements would be most helpful in sensing the very informative distance cue known as "height in the field" (Philbeck & Loomis, 1997; Ooi, Wu, & He, 2001).

Two types of distance judgment were collected for each viewing condition, verbal report and visually directed walking. The judgments were collected in 4 separate blocks of trials (2 viewing conditions × 2 responses) from each observer. Within each block, observers responded three times to each target distance of primary interest (2, 6, and 12 m) with random selection, and one time to each of the remaining distances, dispersed among these trials. For the verbal judgment, observers reported the target distance in feet and inches. For the motor judgment, observers viewed the target, closed their eyes, and then attempted to walk to the location of the target (which was silently removed in the meantime). After making the response, observers closed their eyes and were guided back to the origin. Observers did not receive training for the two types of judgment nor any feedback about the accuracy of their responses during testing. The entire session lasted about 45 min.

3 Results

For each observer, a measure of indicated distance was obtained for each of the six target distances, two levels of FOV, and two types of judgment. For the distances of 2, 6, and 12 m, the measure was the mean of the values on the three repeated trials; for the remaining distances of 3, 10, and 15 m, the measure was the value obtained on the single trial. Overall, indicated distance for reduced FOV averaged 96.6% of indicated distance for full FOV (94.4% for motor and 98.8% for verbal). A two-way (2 levels of FOV × 6 levels of distance) repeated-measures Analysis of Variance was performed separately on the motor and verbal data. For the motor judgment, there was a highly significant effect of target distance, $F(5, 5) = 247.47$, $p < .001$; neither FOV nor the two-way interaction was significant at the .05 level. For the verbal judgment, there was again a highly significant effect of target distance, $F(5, 5) = 13.23$, $p < .001$, but neither FOV nor the two-way interaction approached significance. Figure 3 gives the mean responses of the 10 observers for the two viewing conditions and two types of judgment.

4 Discussion

The results presented in Figure 3 and the null effects of the FOV manipulation in the statistical analysis indicate that reducing FOV to the size used in this experiment produced no reliable underestimation of distance. The implication is that the limited FOV of typical HMDs is not the cause of the large underestimation of egocentric distance seen in several studies of distance perception in virtual environments.

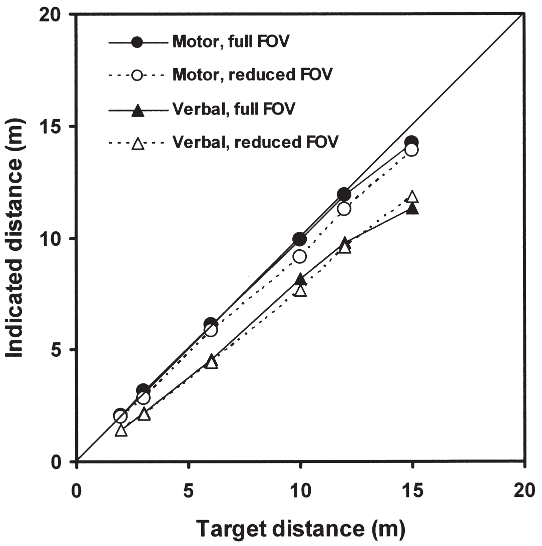

Figure 3. *Results of the current experiment.*

Caution is required in generalizing the null effect of FOV observed here. As mentioned earlier, two reaching studies have found that reduced FOVs comparable to the FOV used here did produce small but reliable underreaching to targets (Bingham & Pagano, 1998; Watt et al., 2000). Also, Kline and Witmer (1996) found that limiting vertical FOV when the head was stationary produced a significant underestimation of distance for moderate distances like those used in this experiment. Because Kline and Witmer obtained a large effect in their study and no effect was obtained here, it is useful to distinguish between "instantaneous FOV," as set by the simulated HMD, and "effective field of regard," which is determined by the instantaneous FOV sweeping out a larger region of space as the head moves. Even when head movements are allowed, it would seem that instantaneous FOVs much smaller than the FOV used here are likely to produce underestimation for the larger distances used in this experiment.

Because FOV does not explain the large underestimation of distance observed in several studies of distance perception in virtual environments, other factors must be involved. One candidate factor is a mismatch between accommodative distance and simulated-object distance, for Bingham et al. (2001) found that the discrepancy between accommodative distance of their HMD and the simulated-target distances resulted in slight overreaching to near targets; it is possible that a discrepancy in the opposite direction could produce underestimation of much larger distances, like those studied here.

Another candidate factor seems to have been ruled out by the recent findings of Thompson et al. (in press) and Willemsen and Gooch (2002) showing that rendering fidelity had no effect on distance perception in a virtual environment. As mentioned earlier, other candidate factors include the dynamic range and spatial resolution of the display and the observer's knowledge of being in a simulated environment. It is possible that a number of relatively subtle factors (display resolution, field of view, rendering fidelity) can combine to produce the observed errors in distance perception. Clearly, more research is needed to determine the cause of the large underperception of distance.

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