Poster Compendium, Proceedings of IEEE Virtual Reality 2008, Reno, Nevada, USA, March 8–12, 2008, pages 267–268.

The Effects of Virtual Reality, Augmented Reality, and Motion Parallax on Egocentric Depth Perception

Adam Jones **J. Edward Swan II** **Gurjot Singh** **Eric Kolstad**

Mississippi State University, Mississippi, USA

1. Introduction

A large number of previous studies have shown that egocentric depth perception tends to be underestimated in virtual reality (VR) — objects appear smaller and farther away than they should (see Swan et al. [1] for a literature review of the claims made in this paragraph). Various theories as to why this might occur have been investigated, but to date the cause is not fully understood. A much smaller number of studies have investigated how depth perception operates in augmented reality (AR), and some of these studies have also indicated a similar underestimation effect.

In this poster we report an experiment that further investigates these effects. The experiment compared VR and AR conditions to two real-world control conditions, and studied the effect of motion parallax across all conditions. Our combined VR and AR head-mounted display (HMD) allowed us to develop very careful calibration procedures based on real-world calibration widgets, which cannot be replicated with VR-only HMDs. To our knowledge, this is the first study to directly compare VR and AR conditions as part of the same experiment. This experiment is reported in detail in the first author's master's thesis [2].

2. Methods

We utilized an nVis nVisor optical see-through AR HMD, which converts to a VR HMD by attaching a small plastic cover. We attached an Intersense IS-1200 optical / inertial tracker to the HMD to obtain the 6 degree-of-freedom attitude of the observer's head. We measured egocentric distance judgments with a *blind walking* protocol, which has been widely used in depth perception research [1]. Figure 2 shows how we implemented blind walking: our experimental apparatus fit on a rolling cart, which we pushed behind the observer as they walked. We conducted the experiment in a long, wide hallway (Figure 4). Observers listened to white noise to mask potential audio depth cues.

We carefully calibrated the HMD for each experimental condition (see Figure 4). We measured the inter-pupilary distance and eye height of the observers, and then placed the display on their head. Observers first ensured that they were looking through the middle of the HMD's optical axis by aligning concentric circles in each eye. Observers next ensured that their optical axis was parallel to the floor by looking down the hallway and aligning a virtual cross in the center calibration circle with a real-world cross placed at their eye height on a distant door. Then, observers corrected for tracker errors; these inevitably arise both from the accuracy limits of physical measurements, as well as from differences in the way the HMD sits on different people's heads. Observers first corrected for x, y, z positional errors by aligning a 2D x-shaped widget (position controlled by the tracker) with the central cross (Figure 4). Observers next corrected for *roll*, *pitch*, *yaw* rotational errors by aligning the 3D widget shown in Figure 1 (rotational attitude controlled by the tracker) with the central cross. As indicated by the bottom row of Figure 4, the 3D shape of this widget is such that when the rotational attitude is correct, the z-axis collapses and the widget looks like a 2D cross. This makes the widget sensitive and easy to use; we believe this widget is a novel contribution to rotational AR calibration techniques.

Our experiment examined two viewing conditions: (1) a *virtual reality* condition (the virtual referent object appeared in an accurate virtual model of the experimental hallway), (2) an *augmented reality* condition (the virtual object appeared in the real-world hallway); and two control conditions: (3) a *real world + HMD* condition (observers wore the HMD, which displayed no graphics, and saw a real-world referent object that appeared in the real-world hallway), and (4) a *real world* condition (as above, but observers did not wear the HMD). Crossed with these were two *motion parallax* conditions: (a) observers stood still, and (b) observers rocked back and forth, shifting their weight from foot to foot, which induced motion parallax. Observers saw referent objects positioned at 3, 5, and 7 meters; noise trials (25%) were randomly positioned between 2.5 and 8.5 meters. Our factorial design was completely within-subject, and was counterbalanced with Latin squares and random permutations. Our experiment yielded 16 observers × 4 environments × 2 parallax conditions × 3 distances × 2 repetitions = 768 data points (1024 data points including the noise trials).

3. Results

We examined both *judged distance* and *normalized error* = *judged distance* / *veridical distance*; *normalized error* expresses the judged distance as a percentage of the correct distance. Figure 5 shows the main results; for clarity they are offset and grouped by environment. These results show a general trend of underestimation. However, Figure 3 shows that the observers 1, 6, and 13 underestimated to a much greater degree than the rest of the observers. Figure 6 shows the results with these observers removed; we believe that these are the most generalizable results.

Based on the results shown in Figure 6, observers performed veridically in the real-world condition (*normalized error* = 98.1%), which indicates that we properly implemented the blind walking protocol. Observers also performed veridically in the AR condition (99.3%), but showed a significant (yet historically small) underestimation effect in VR (93.3%). This suggests that part of the VR underestimation effect is caused by the VR background. The only effect of motion parallax occurred for the real-world HMD condition, which showed a significant difference between the still (98.3%) and motion (91.5%) conditions. This is consistent with other studies (see citation in [1]) which suggest that the mass and inertia of an HMD affects depth perception, but it is curious that the effect only occurred in the real-world HMD condition.

References

[1] Swan II JE, Jones A, Kolstad E, Livingston MA, and Smallman HS, "Egocentric Depth Judgments in Optical, See-Through Augmented Reality", *IEEE Transactions on Visualization and Computer Graphics* (TVCG), 13(3), 2007, pp. 429–442.

[2] Jones A, *Egocentric Depth Perception in Optical See-Through Augmented Reality*, Master's Thesis, Mississippi State University, 2007.

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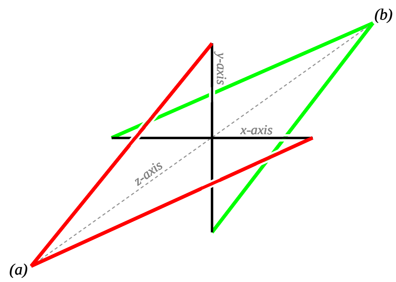

Figure 1: Rotational calibration widget seen in bottom row of Figure 4.

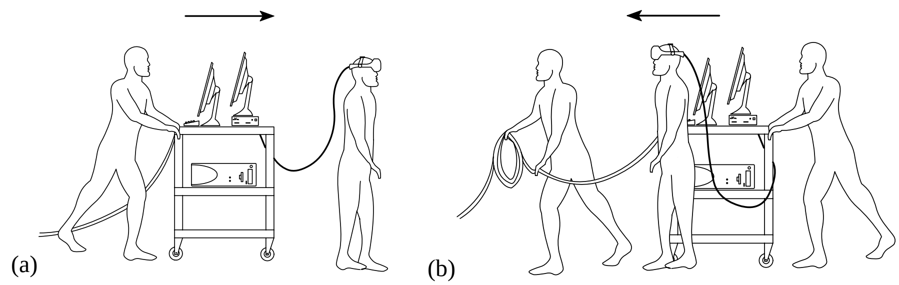

Figure 2: Our implementation of blind walking for the head-mounted display (HMD) conditions. (a) Computer cart pushed behind observer during the walk. (b) Returning to starting position.

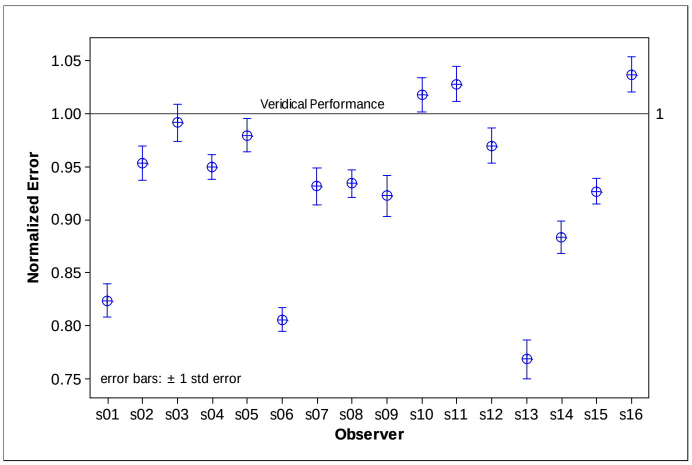

Figure 3: The normalized error per observer (N = 1024). Based on this analysis, we removed observers 1, 6, and 13 from Figure 6.

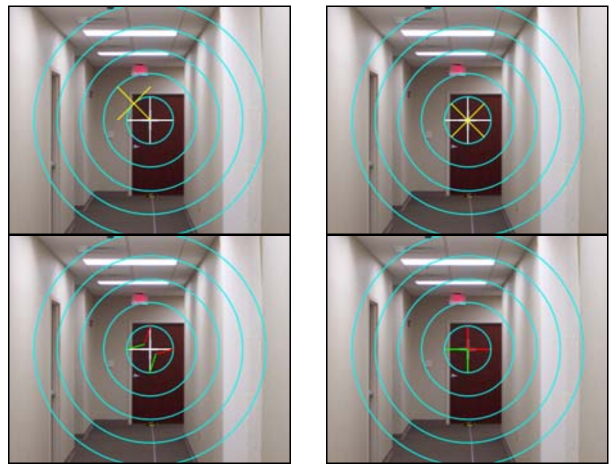

Figure 4: Observer's view of tracker calibration widgets. (upper row) Positional calibration. (lower row) Rotational calibration. (left column) Uncalibrated view. (right column) Calibrated view.

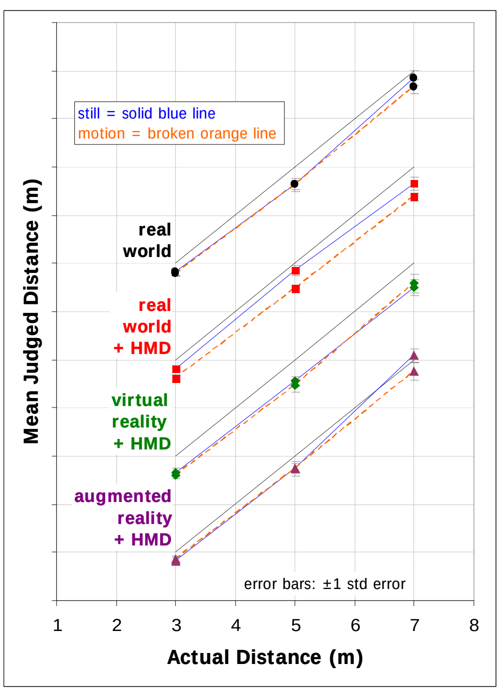

Figure 5: Depth judgments over all observers (N = 768). The diagonal lines are veridical; the results are offset for clarity.

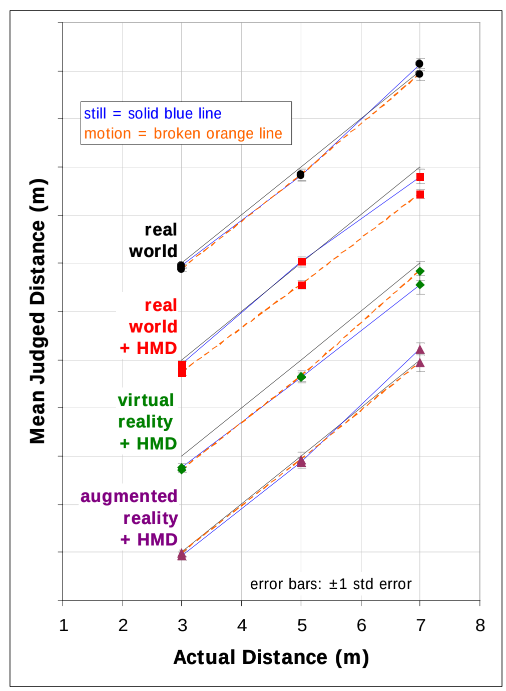

Figure 6: Depth judgments with underestimating observers 1, 6, and 13 removed (N = 624); see Figure 3.