Methods for Evaluating Depth Perception in a Large-Screen Immersive Display

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ABSTRACT

We perform an experiment on distance perception in a large-screen display immersive virtual environment. Large-screen displays typically make direct blind walking tasks impossible, despite them being a popular distance response measure in the real world and in head-mounted displays. We use a movable large-screen display to compare direct blind walking and indirect triangulated pointing with monoscopic viewing. We find that participants judged distances to be 89.4% ± 28.7% and 108.5% ± 44.9% of their actual distances in the direct blind walking and triangulated pointing conditions, respectively. However, we find no statistically significant difference between these approaches. This work adds to the limited number of research studies on egocentric distance judgments with a large display wall for distances of 3-5 meters. It is the first, to our knowledge, to perform direct blind walking with a large display.

CCS CONCEPTS

• **Computing methodologies → Perception**; *Virtual reality*.

KEYWORDS

Large-Screen Immersive Displays; Distance Perception; Virtual Reality; Immersive Virtual Environments

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1 INTRODUCTION AND BACKGROUND

Immersive Virtual Environments (IVEs) have numerous applications including entertainment, training, prototyping, and research. To toss a virtual ball to a simulated avatar, for example, you need to accurately perceive a distance and act upon it. While many studies have examined distance judgments in real environments and head-mounted displays, fewer studies have examined egocentric distance judgments in large-screen displays (for a review, see [9]). Egocentric distances are those between oneself and an observed point, rather than between two observed points. Large-screen displays present a unique challenge because the most common way to measure perceived distance, direct blind walking, requires participants to walk to a previously seen target. However, if the screen is not movable, participants can't walk through the screen to reach targets beyond the screen. As far as we know, our study is the first to examine direct blind walking with a movable large screen. This work compliments the numerous real-world and HMD-based studies that use the same technique. The results are compared to a triangulated pointing task with a fixed screen.

There are several methodologies for measuring perceived egocentric distances in real and virtual environments. Since any one methodology may be biased in various ways [6, 9], it is important to consider different approaches. If multiple methods produce similar (or different) results, this can help improve our understanding of human perception. One class of methods involves visually directed actions where participants view a target and then perform a physical action which is based on the target distance. One of the most popular techniques, direct blind walking, involves displaying a target and having the participant close their eyes and walk the distance to the target [9]. This technique is typically impractical with large-screen displays because the screen itself is in the participant's walking path. Another action-based walking technique is triangulated blind pointing. With this response measure, participants walk to the side a short distance and then turn and point at the target position [2, 5] or take a few steps toward the target [10]. The indicated distance can be calculated by intersecting the participant's original line-of-sight to the target with the line they create by pointing. Triangulated blind pointing was shown to be accurate in the real world by [3]. This technique also can be performed with large-screen displays, and one study by [5] found that underestimation occurs. In IVE systems where tracking space is limited, this method also has the benefit of allowing participants to indicate distances beyond what the space might support for direct walking. Further, it may also be supported by large-screen displays with sufficient space around the screen.

There are also other methods of measuring distance judgments with large screens. For example, in timed imagined walking, participants start a stopwatch and imagine walking to the target, stopping it when they imagine they are at the target. Evidence suggests that timed imagined walking is underestimated in large-screen displays [4, 5, 8]. With verbal reports, participants verbally indicate the distance to the target in their preferred units (e.g. feet or meters) [5]. However, verbal reports may be biased by cognitive influences [7]. One study examining verbal reports with a large-screen display [1] found that people overestimated 2m distances

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and underestimated distances beyond 3.5m while verbal reports in a similar real environment were more consistently accurate.

2 EXPERIMENT

We chose to examine two action-based response measures which involve walking with our movable large-screen display: blind direct walking (Direct) and triangulated blind pointing (Triangulated). These response measure varied between participants.

Participants viewed the virtual environment on eight 46-inch Samsung LED displays (two screens wide, four screens tall) with 1080p resolution. Each screen had a one half centimeter border along the perimeter, leaving a one centimeter black border between screens, as seen in Figure 1. These screens were not capable of displaying stereo images.

Participants' locations were measured using Vicon Tracker software and 12 Vicon MX T20-S cameras operating at 100 Hz. The system tracked multiple reflective markers placed on a hat worn by each participant. In the Triangulated condition the system also tracked markers on a small object that participants held and used to point to the target.

2.1 Blind Direct Walking Condition

2.1.1 Method. Prior to the experiment, participants signed an IRB consent form, completed a questionnaire, and had their eye-height measured. Participants were given verbal and written experiment instructions. The experimenter assisted participants while they walked blindfolded in a hallway to familiarize them with blind walking. Participants also wore an eye patch over one eye because our display was not capable of displaying stereo images. Participants chose which eye to use and we verified that their chosen eye had at least 20/30 acuity with a Snellen eye chart. They also wore headphones playing white noise to mask ambient noise and a blindfold. The blindfold was worn over the eye patch and the participant could move it to their forehead when viewing the virtual room and target.

Participants were blindfolded before being brought into the lab to prevent them from seeing the physical environment. Once the participants were positioned in front of the display, they placed the blindfold on their forehead and viewed the virtual scene. Participants were positioned 1 meter from the display and offset 26 centimeters to the right of center so the targets were not located on the black border between the left and right screens. This created a horizontal field of view 52.1 degrees to the participants' left and 37.4 degrees to their right. The display's bottom was 26.5 centimeters above the floor and it extended vertically 2.31 meters. The vertical field of view depended on participant eye height and ranged from 95.7 to 98.0 degrees. The graphics frustum was adjusted based on the participant eye height to ensure that the virtual scene was displayed correctly for their eye position. Eye heights were manually measured instead of using the tracking system since we felt it would be more accurate given that the offset from the tracked hat to the eyes would differ between participants.

For each trial, participants were allowed to view the target for as long as they liked and were only allowed to rotate their head. They were instructed to 'get a good mental image' of the target's location. Once they were ready, participants put their blindfold on and were instructed to wait while we moved the display out of their way. On average, this wait lasted about eight seconds. Participants' starting positions were then recorded using the tracking system and they were instructed to walk to where they thought the target was located. Once the participants had stopped, their final locations were recorded as well. Participants were then led back to the starting location for the next trial. The starting location was fixed at a known location and marked with a piece of tape on the floor mimicking most real-world distance judgment experiments. By recording the starting position, we were able to measure how accurately we placed participants at the fixed location.

Participants completed two practice trials before beginning the experiment. They then completed 12 evaluation trials and three additional practice trials in a randomized order. Each evaluation trial had a target distance of 2, 3, 4, or 5 meters. The order of the evaluation trials was randomized for each participant, but they always completed three trials at each target distance. Distances with half-meter offsets (e.g. 3.5 meters) were used for all practice trials to prevent participants from becoming too familiar with the evaluation distances. The targets used were colored shapes that were randomly selected from a pool for each trial.

2.1.2 Participants. Twelve people, recruited via convenience sampling, participated in this condition (7 male, 4 female, and 1 non-binary) and ranged from 19 to 32 years of age. 4 participants reported having never used VR before, 4 had used it once or twice, and 4 reported using it occasionally (a few times per year). All participants that reported previously using VR indicated that they had used a commercially available head-mounted display. 10 participants chose to use their right eye for the experiment, while the other 2 used their left. Participants received $10 compensation for their participation.

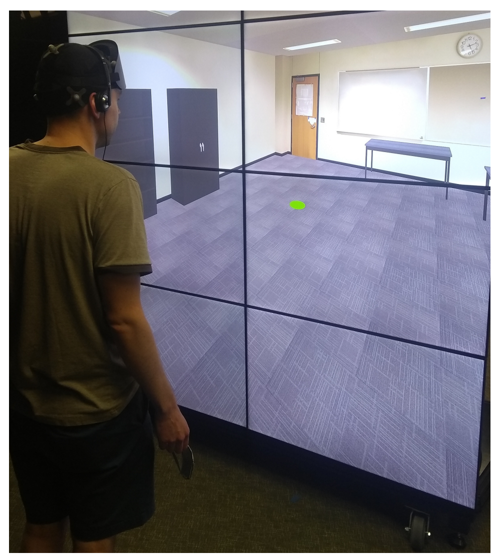

Figure 1: The large-screen display utilized for the experiment. The person is holding a tracked marker utilized in the Triangulated condition. The lights were further dimmed or turned off during the experiment.

2.2 Triangulated Blind Pointing Condition

2.2.1 Method. Participants completed the same pre-trial procedure as in the DIRECT condition. Participants also stood in the same location in front of the display, creating an identical horizontal field of view. The participants' eye heights in this condition created a vertical field of view that ranged from 96.0 degrees to 98.0 degrees.

During each trial, participants were again allowed to view the target as long as they liked. Once they were ready, they were instructed to turn their body 60–70 degrees to the right while keeping their head directed at the screen. They then placed the blindfold over their eyes and waited eight seconds, to match the average in the DIRECT condition. Once the time was up, the experimenters instructed the participants to walk forward. Participants walked until told to stop, which was at a location approximately 3.5 meters from their starting position. This distance was chosen to minimize the error in indicated distance caused by any angular error in participants' pointing, as the evaluation distances ranged from two to five meters. The average measured distance participants walked was 3.69 meters. Participants were instructed to stop and turn towards the target, optionally take a step or two towards it, and point in the direction of the target with a tracked object. The locations of the participant's head and the object they held were recorded for each trial using the tracking system.

2.2.2 Participants. A total of 12 people participated in this condition, none of whom participated in the previous condition. They were also compensated $10 for their participation. There were 7 male and 4 female participants with one choosing not to answer. Their ages ranged from 19 to 24 years. Of the participants in this condition, 5 reported using VR once, 6 reported never using it, and one reported using it occasionally. All participants that reported using VR indicated that they used a commercially available head-mounted display. In this condition, 8 participants elected to use their right eye, and the remainder used their left.

3 RESULTS & DISCUSSION

On three occasions, two participants in the TRIANGULATED condition pointed in a direction that failed to produce a comprehensible distance. Specifically, after walking to their right, they pointed too far right to create an intersection in front of them with the virtual line between their starting position and the target. [5] reported similar problems with their experiment and described an interpolation process to fill in the missing data. After looking more closely, we found that both of these participants also indicated distances that were excessively large (e.g., over 50 meters) in at least one other trial. Therefore, we excluded these two participants and used the remaining ten participants in the analysis.

We first calculated the average distance indicated for each of the four target distances. For the TRIANGULATED condition, we calculated this distance by intersecting the line between the fixed starting location and the target with the line between the participant's ending head location and the object they used to point. The tracking system measured the participant's head location and point object location. The average indicated distance for both conditions can be seen in Figure 2. We ran a Shapiro-Wilk test on each target distance for each condition and all tests showed normality ($p > 0.05$) except for the 3 meter distance in the TRIANGULATED

Figure 2: Average indicated distance for the two conditions compared to the veridical (true) target distance. Error bars denote standard error of the mean.

condition, which had $p = 0.041$. Since removing two participants from the TRIANGULATED condition made the results unbalanced, we performed a type III ANOVA for our 4(target distance)x2(condition) mixed design. The between-subject condition variable (DIRECT and TRIANGULATED) did not significantly impact participant's distance judgments ($F(1, 20) = 1.80, p = 0.19$). As expected, the target distance significantly impacted the distances indicated by participants ($F(3, 60) = 50.00, p < .01$). There was no significant interaction between the two variables ($F(3, 60) = 0.75, p = 0.53$).

Another way to look at the data is to collapse all of the responses into a percentage relative to the displayed target distance. When we do this, we found that participants indicated that the targets were 89.4% ± 28.7% and 108.5% ± 44.9% of their actual distances in the DIRECT and TRIANGULATED conditions respectively. The uncertainty is represented by the standard deviation, as calculated using each participant's average performance for each target distance.

In TRIANGULATED pointing, asymmetric errors will occur if the participant points farther to the left or right than intended. For example, a pointing error where a participant points too far to the right will cause a larger change in their indicated distance than one where they point too far to the left. Since the errors from triangulated pointing may not be normally distributed, traditional statistics like those that we performed are not ideal.

Like most distance judgment experiments, we brought participants to a starting position that was marked with tape on the floor and measured the indicated distance from this point. Incorrect placement, along with any error in the measured eye height, could have led to the target being displayed incorrectly. We measured the participants' starting positions with our tracking system to quantify how accurately we placed each participant. We found that the average lateral placement error was 5.7 cm and the average posterior/anterior error was 10.0 cm. This may have been inflated by participants turning in the TRIANGULATED condition before their starting position was measured. In the future, we hope to dynamically draw the correct graphics on the screen based on the participants' starting location before they open their eyes. Other potential sources of error include misplacement of the screen and small errors from imperfect tracking system calibration.

Our triangulated pointing procedure was modeled after a [10] HMD study. However, [5] used a slightly different triangulated pointing procedure for a large-screen display study. While we found people indicated distances that were 108.5% of veridical, Klein et al. found percentages closer to 50%. In their study, people viewed a large display on a wall, turned 90 degrees, walked forward, and then dropped a beanbag in the direction to the target. The screen itself was also significantly different. Ours was visibly portable (on wheels). Participants could also see the edge of the screen in the direction that they were walking and could likely see in the darkened lab that once they walked past the edge of the screen, they would be able to walk behind it (i.e., the screen wasn't as wide and wasn't part of a larger wall), which may have reduced the immersiveness of the display. Additionally, our screen was incapable of producing stereo images while Klein et al. used two projectors to do just that. However, more work is needed to determine why our triangulated pointing condition produced results significantly different from Klein et al.

In a post-study questionnaire participants were asked to rate a few statements on a seven-point Likert scale where 7 was strongly agree. For the statement 'I felt like I was in the virtual room', participants' mean rating was 5.2 in the Direct condition and 4.7 in the Triangulated condition. For the statement 'I felt confident in my size or distance judgements' participants' mean rating was 5.3 in the Direct condition and 5.2 in the Triangulated condition.

4 LIMITATIONS AND FUTURE WORK

The display that we used in this experiment was not capable of displaying stereo images. Though we were able to combat the biasing effects of this by having participants wear an eye patch, it would be helpful to study the effects of stereo vision on virtual environment distance judgments. Additionally, our display was made up of eight different screens that contained small black borders, interrupting the virtual environment. Occasionally, some of these borders partially covered the target and may have served as landmarks for the participants to use. The screen also did not reach the floor, which could have made it harder for participants to identify the relationship between the real and virtual floors. As reported in the results section, participants were on average near-neutral about whether they felt as though they were in the virtual room, which may have impacted their ability to effectively judge the distances.

In the Direct condition, participants may have been cautious with walking since they always had a screen in front of them while they had their eyes open. HMD and real-world studies using direct blind walking do not have a similar problem. Our experiment, like many, tried to mitigate this by practicing blind walking with the participant prior to the experiment. The Direct condition also required participants to wait a short period of time between seeing the target and being able to walk to it. Although we mimicked this in the Triangulated condition, it may be interesting to manipulate this wait time as an independent variable.

Although there was no statistically significant difference between the Direct and Triangulated conditions, this study had a limited number of participants. Further, statistical analysis of the asymmetric errors that occur with triangulated pointing make it challenging to perform statistical tests correctly. Additional work with more participants may show that there is a difference between the two measurement techniques. In the future, we would also like to explore a condition without a display that takes place in the physical lab that the virtual lab was modeled after.

In open comments on the post-study questionnaire, one participant in the Triangulated condition stated that 'the sense of space felt odd' due to the dimensions of our virtual room. The participant elaborated that since they were walking to the side, they felt like they might run into a table that was near the side wall in the virtual room. Future studies could address this issue by creating environments that vastly exceed any required walking distance.

5 CONCLUSIONS

As far as we know, this study is the first which uses a direct blind walking distance judgment task with a large-screen display. This work adds to the limited amount of research on egocentric distance judgments beyond reaching distances. Overall, we found no significant difference between the two conditions, which suggests that both methods are acceptable ways to perform egocentric distance judgements. However, the Triangulated condition had a higher standard deviation, which shows that it may be a less consistent method. Our direct blind walking results where people judged distances to be 89.4% are reasonably consistent with large-screen and CAVE timed imagine walking studies finding percentages of 60 [5] to 85% [4] for similar target distances. However, our triangulated pointing judgments were notably different than those found by [5], but variations in procedure and display may have contributed to those differences.

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