A Conceptual Replication and Extension of Triangulation by Walking for Measuring Perceived Distance Through a Wall

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Abstract

Triangulation by walking is a method that has been used to measure perceived distance, where observers walk a triangular path. This method has been used at action space distances of approximately 1.5 to 30 meters. In this work, a conceptual replication of these triangulation by walking methods are discussed and evaluated for use in measuring the perceived distance of an object seen through a window set into a wall. The motivation for this work is to use triangulation by walking to study how perceived distance operates when augmented reality (AR) is used to visualize objects located behind opaque surfaces, in an AR application termed "x-ray vision." This paper reports on experiences replicating an implementation of triangulation by walking as reported by Fukusima, Da Silva, and Loomis (1997). Their method was conceptually replicated in both outdoor and indoor settings, and the method was further extended to measure perceived distances of objects seen through a wall. These extensions are discussed in some detail, focusing on the modifications to the triangulation by walking method as well as the ramifications of these changes. Problems arising from using triangular geometry in calculations of perceived target locations are also introduced, and an alternate method is proposed that works to diminish the problematic effects.

Index Terms: distance perception—x-ray vision—triangulation by walking—replication

1 Introduction

In augmented reality (AR) *x-ray vision*, observers are able to see beyond opaque surfaces that would normally occlude their view to content beyond those surfaces. AR x-ray vision has primarily been studied in the context of AR image-guided surgery and similar medical applications [7], where tasks occur within *reaching space distances* of about 1.5 meters or less. However, many interesting AR x-ray vision tasks occur within *action space distances*, which range from approximately 1.5 to 30 meters, including remote robotic navigation, exploring a smoke- or steam-filled environment, and evaluating a closed-off room or environment for hazards [11]. Perception operates differently at action space distances than it does at reaching space distances [2], necessitating a careful study of the perceptual effectiveness of x-ray vision in action space.

One of the applications for which x-ray vision at action space distances is critically important is the *room-clearing scenario* [12]. In this scenario, a police team must enter a room without complete knowledge of the room's contents or potential dangers. Room clearing is potentially dangerous and very stressful, but if the officers have good *situation awareness* of the room's contents, then planning is improved and stress is reduced. As such, better situation awareness may be associated with improved outcomes, and its relationship with x-ray vision should be further examined.

The theoretical underpinnings of situation awareness [4] span a range of neural phenomena, from cognitive to perceptual. These range from higher-level emergent features, such as prediction and comprehension, to very low-level features, including perception itself. For situation awareness, perception represents the foundation from which the higher-level properties stem; in the context of the room-clearing operation, then, improved perception is critical.

This naturally leads to the question of how to experimentally test and evaluate perception in x-ray vision tasks, but, first, it is necessary to discuss how x-ray vision might be implemented. In order to create an AR x-ray vision experience, observers wear an AR head-mounted display, the Magic Leap One, and face a solid opaque wall. The AR device supplements real-world vision with location-specific graphics; these graphics visually resemble a virtual window in the opaque wall through which hidden information can be seen. In this context, the hidden information is the content of the room beyond the opaque wall. This should allow observers to understand the environment of the room beyond the wall; the main question now is how well understood that information is.

In assessing this, one of the most significant and basic components of perception is perceived object location. This metric can be represented as a perceived distance and a perceived direction that together inform the perceptual location of an object. For many AR tasks, perceived direction is generally trivial, but perceived distance has often been found to deviate substantially in AR environments [8, 13, 14]. AR distance perception remains an active area of research, and experimental testing demonstrates a variety of methods and approaches.

To date, one of the most successful and replicated methods for measuring perceived distance in action space has been *blind walking* [8], where observers perceive an object at a certain distance, and then cover their eyes and walk until they believe they are at the object's location. This technique has been widely applied to augmented reality [13, 14], but it requires a clear path from the observer to the object. For x-ray vision tasks, observers are positioned in front of a solid wall and so direct blind walking is not an ideal methodology in this use case.

However, the *triangulation by walking* method, as described by Fukusima, Da Silva, and Loomis [5], represents a usable approach to measuring perceived distance. As shown in Figure 1, in triangulation by walking the observer stands at the origin, looks at the target, and then closes their eyes, turns and walks obliquely to the left or right. When the observer reaches the turning point, marked at 4 or 6 meters in Figure 1, the experimenter instructs them to turn and walk toward the target. After taking several steps toward the target, the experimenter instructs them to stop. In experiment 4 of Fukusima et al. [5], which was conceptually replicated for this research [11], the

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This is an author version preprint. The final version is available as: Nate Phillips, Farzana Alam Khan, Mohammed Safayet Arefin, Cindy L. Bethel, Jeanine Stefanucci, J. Edward Swan II, "A Conceptual Replication and Extension of Triangulation by Walking for Measuring Perceived Distance Through a Wall", In *Workshop on Replication in Extended Reality* (WoRXR), *IEEE International Symposium on Mixed and Augmented Reality Adjunct Proceedings* (ISMAR-Adjunct), October 17–21, Singapore, 2022, pages 278–282. DOI: 10.1109/ISMAR-Adjunct57072.2022.00063.

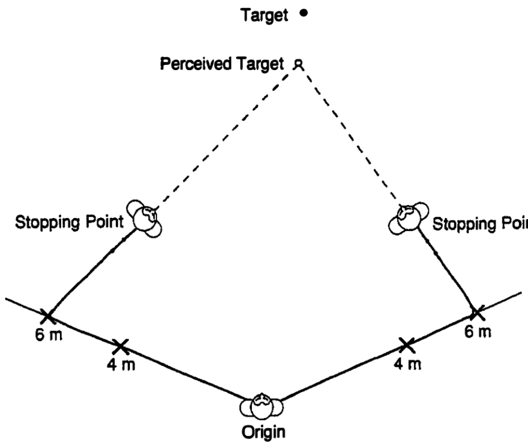

Figure 1: The *triangulation by walking* method [5]. The perceived target is the intersection of a left and a right blind triangular walk. This is the *left-right* method of calculating the perceived target location.

observer stood at the origin, facing the right or left turning point, and looked sideways at the *target*—a yellow rectangular object mounted on a tripod and set to the height of the observer's eyes. The observer was always instructed to turn after a walk of 5 meters. The observer wore a 2-meter long heavy chain, and after the observer stopped, standing with their eyes closed, the experimenters placed two golf tees in the grass along the chain, indicating the observer's vector pointing towards the perceived target. Observers made two such walks in quick succession, first to the left and then to the right, or vice versa. Then, while the observer stood with their back to the experimental area, the experimenters measured the position of the 4 marked locations. To make this measurement, an ultrasonic distance measuring device determined the distance between each golf tee and two fixed calibration points. The 2-dimensional coordinates of each marked location were then determined by *trilateration* [10], a method from surveying. As shown in Figure 1, the perceived target location was defined as the intersection of the vectors formed from the observer's left and right walks. In the rest of this paper, this is referred to as the *left-right* method of calculating the perceived target location.

In a direct comparison, Fukusima et al. [5] found that blind walking and triangulation by walking resulted in equivalent perceived distances. In contrast, this research used triangulation by walking to measure the perceived distance of a target object seen through a window set into an opaque wall. Here, the observer at the origin looks through a window which was either real or virtual, and the edge of the wall is positioned so that the triangulated walk can go around the edge. This method was compared to a control condition where there was no wall. The target was either real or virtual and seen through an AR display. Triangulation by walking was conceptually replicated in both outdoor and indoor settings[1]. In the rest of this paper, these replications are discussed, with a particular focus on explaining the changes made to the method and the lessons learned.

2 Outdoor Replication

2.1 Method

The outdoor replication was based on the method of experiment 4 from Fukusima et al. [5], as described above. It can be categorized as a *conceptual replication* [3], because some aspects of the method were changed, as described here.

Location. The original experiment from Fukusima et al. [5] was conducted on a flat grassy field, and golf tees were used to mark

[1]Results are presented in the first author's PhD dissertation [11].

Figure 2: The outdoor replication setting was a flat, empty parking lot. This is the view from the observer's *start point* (Figure 3).

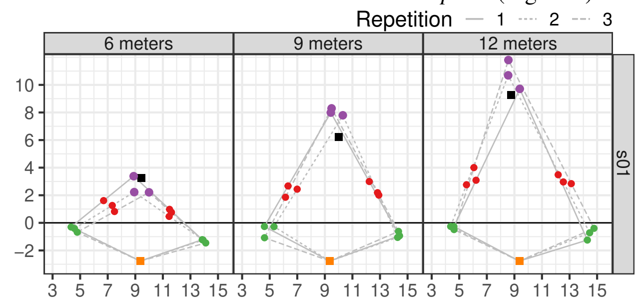

Figure 3: For the outdoor replication, a top-down view of the paths walked by observer "s01". Black squares indicate the target. Purple dots indicate the perceived targets, as calculated by the *left-right* method (Figure 1). Walked paths begin at the *start point* (orange square), proceed to the *turn point* (green circle), and then to the *stop point* (red dot). The $x-$ and $y-$axes are marked in meters. From Phillips [11].

locations. A grassy field that was flat enough or large enough could not be found, so a large, flat section of a parking lot was used instead (Figure 2).

Distances. The original experiment from Fukusima et al. [5] tested target distances of 6, 12, 18, and 24 meters. In order to better match the room-clearing scenario, shorter distances of 6, 9, and 12 meters were tested. This replicated two of the original experiment's distances and added the distance halfway between them.

Target. The target object was changed to a tall soft-drink can placed on the ground (Figure 4b). This target object was chosen because the Magic Leap One AR display could render the same object, and the size and position of that object could be readily verified. To perform this verification, the virtual target was rendered on top of the real target, and then viewed from all angles, ensuring that the virtual and real targets remained aligned.

Measuring Positions. To indicate the vector between the turning point and stopping point, observers in Fukusima et al. [5] dragged a heavy chain. This was evaluated for the replication, but the weight of the chain made walking seem unnatural. Furthermore the replication occurred during the COVID-19 pandemic, during which the idea of multiple observers handling the same chain was not desirable. Instead, when observers reached the turning point they were instructed to stop and turn to face the target, keeping their eyes closed. While stopped, an experimenter placed a small Hacky Sack beanbag behind their feet (Figure 5a). Beanbags were found to work well, because the beans made the bag fall with a thud and stay put. Therefore, the experimenter could gently toss the bag into position, and the whole process only took a few seconds. A second beanbag was positioned when the observer reached the stopping point. To measure beanbag positions, the ultrasonic distance measuring device from Fukusima et al. [5] was used.

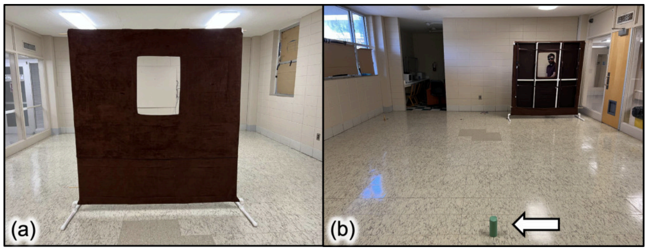

Figure 4: The indoor replication setting: an empty room. (a) The experimental wall. (b) Observer behind the wall, looking at the target object (arrow). The observer and wall are in position for a triangulated walk to the right. Relative to Figures 6, 7, and 8, the foreground of the photo is at the top of the graph.

2.2 Results

Figure 3 shows the paths walked by one outdoor observer. The observer stood at the *start point* (orange square), blindly walked to the *turn point* (green circle), and then turned to face the target. After their position was marked with a beanbag, they walked to the *stop point* (red circle). The left-right method was used to calculate the *perceived target location* (purple circle) for each pair of left and right walks. The actual target location (black square) is shown for each target distance. As shown here, there was generally good agreement between perceived and actual target locations [11]. The outdoor experiment was deemed a successful conceptual replication.

3 Indoor Replication

3.1 Method

Experimental testing was initially evaluated for an outdoor environment. However, neither the Magic Leap One display nor a newer Microsoft HoloLens 2 display was bright enough for outdoor use—the virtual target object appeared dim and insubstantial on a cloudy day and was invisible in sunlight. This is a longstanding issue for optical see-through AR displays [6]. In addition, police team collaborators were interested in indoor room-clearing. Therefore, further experiments were moved into an indoor environment.

Setting. Testing took place in the room shown in Figure 4. A top-down view of this room is diagrammed in the panels of Figures 6–8. The room was 6.25 meters wide ($x-$axis) by 8.20 meters tall ($y-$axis). One wall of the room had windows looking outside, which were blocked to make the lighting consistent regardless of the time of day. The other wall consisted of a floor-to-ceiling window, which look out to an interior corridor.

In this experiment, a mobile wall and window were used, as shown in Figure 4. This wall was constructed of a lightweight opaque fabric stretched over a plastic frame, and the window was positioned so that observers could see the target through the window when standing behind the wall (Figure 4b). When blind walking, observer behavior can be disrupted or biased if they believe that they are too close to a wall or any furniture [15], and therefore it was important to carefully ensure that observers had sufficient space to complete their blind triangulated walks. Therefore, the left and right starting positions were shifted as shown in Figures 6–8. For walks that began by walking right, the wall was shifted to the left of the room and vice versa. In Figure 4b, the wall and observer are positioned for a walk to the right.

Measuring Positions. A nice feature of the indoor room was that the floor consisted of 30.5-centimeter square tiles (Figure 5). Careful measurements indicated that the tiles were laid evenly, and the tile grid could be used to measure object positions. It was like walking on a sheet of graph paper. Each tile was marked with coordinates (Figure 5b). The tape color was a good match for the floor color,

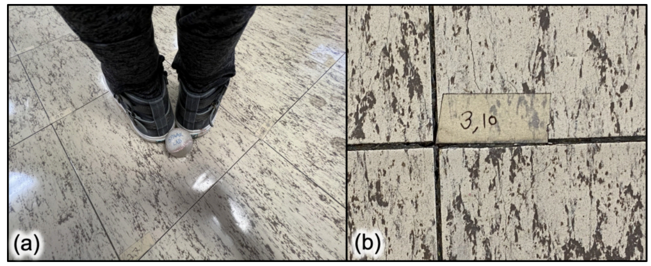

Figure 5: Measuring indoor positions on the tile grid. (a) Placing a Hacky Sack beanbag to mark the position. (b) Tile labels.

and therefore to a standing observer the coordinates were not very salient. To measure positions, the coordinates of the tile containing the beanbag were measured and the tenth digit visually estimated. For example, if the beanbag was located as shown in Figure 5, the estimated coordinates might be 3.7 tiles on the x-axis by 10.4 tiles on the y-axis. This technique had several advantages. First, compared to the outdoor replication, recording positions was much faster indoors. The second advantage arose from consistently thinking about the room geometry in terms of tile units: the wall and target were placed according to tile coordinates, the AR system was calibrated in terms of tile coordinates, and Figures 6–8 were initially rendered in tile coordinates.

Distances. For the indoor replication, three shorter distances were selected in order to fit the experimental room. These distances are shown in Figures 6–8: 3.66, 5.49, and 7.32 meters, which correspond to 12, 18, and 24 tiles. One potential risk with using such a small number of discrete distances was that observers would learn these three locations, and would walk toward their memorized location instead of attempting to perceive the target location. In order to disrupt this pattern, additional distances, referred to here as *confusion distances* (Figure 8), were interspersed alongside the target distances.

Masking Sound Location Cues. The goal of triangulation by walking is to measure the perceived distance and location of the target. Given this, if observers solve the task using information other than their visual perception of target distance and location, the validity of the task is reduced. Fukusima et al. [5] examined whether observers might be using sound location cues from hearing the experimenter's voice to make their judgements more accurate; indeed, examining this question is the purpose of their experiment 4. Although Fukusima et al. did not find evidence that location judgements became more accurate when the experimenter's voice could be heard, subjective experience revealed that when observers' eyes were closed, hearing the experimenter's voice allowed observers to triangulate their position throughout the trial, especially when indoors. This led to a procedural modification that removed the ability of observers to determine the experimenter's position from hearing their voice.

In both indoor and outdoor replications, there were always two experimenters. In the outdoor replication, one experimenter directed the observer, while the other experimenter placed the beanbag. Measuring the beanbag locations took both experimenters, as operating the ultrasonic measuring device required two people. However, recording the tile coordinates indoors only required one person. In addition, the indoor room featured floor-to-ceiling windows along one wall. Therefore, one experimenter remained outside the room, watching and directing the observer through these windows. Observers were encouraged to bring their earbuds or headphones, though sanitized headphones were also available. All observers had a phone, and the great majority also had their own earbuds or headphones. In order to communicate with the observer, the experimenter outside the room called their phone, and the observer listened to the instructions through the corresponding speaker. In this way, the

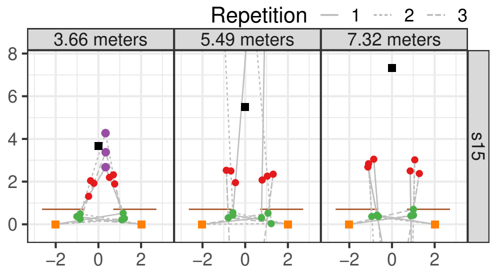

Figure 6: For the indoor replication, top-down view of the paths walked by observer "s15". Perceived targets are calculated with the *left-right* method. Note the perceived targets located at very large distances from the start point (5.49 meters), as well as behind the start point (7.32 meters). Each panel is the size of the experimental room. The brown lines indicate the position of the wall. See the caption for Figure 3. The $x-$ and $y-$axes are marked in meters. From Phillips [11].

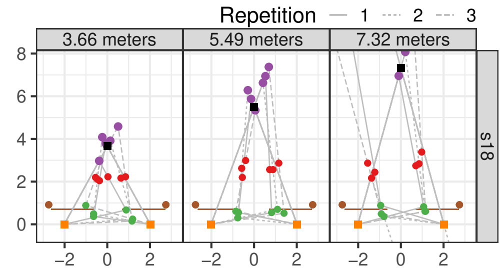

Figure 7: For the indoor replication, top-down view of the paths walked by observer "s18". Perceived targets calculated using the *direct walk* method (see text). Note the perceived targets located at very large distances, as well as behind the start point (7.32 meters). See the caption for Figure 6. The $x-$ and $y-$axes are marked in meters. From Phillips [11].

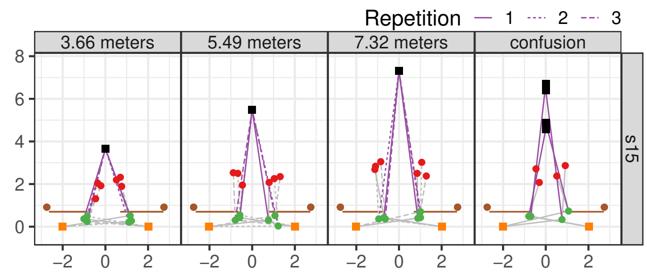

Figure 8: For the indoor replication, top-down view of the paths walked by observer "s15". The *angular error* is the angle between the *turn-target vector* (purple) and the *turn-stop vector*, where the turn-target vector is created by the turn point and the target, and the turn-stop vector is created by the turn point and the stop point. See the caption for Figure 6. The $x-$ and $y-$axes are marked in meters. From Phillips [11].

sound of the experimenter's voice was no longer tied to a specific spatial location in the room and so the potential confound of audio cues from the experimenter was removed.

3.2 Results

Figure 6 shows the paths walked by one indoor observer. As with the outdoor walks, the observer stood at the start point, blindly walked to the turn point, turned to face the target, and then walked to the stop point. The location of both points was recorded. As described above, during walks to the right, the wall was located to the left and vice versa.

Triangular Geometry Problems. In the indoor replication, calculating perceived locations with the left-right method exhibits two problems in producing an accurate distance estimate, as illustrated in Figure 6. Both problems are caused by using triangular geometry to calculate the perceived target location. When the observer turns inward to face the target, their motion indicates an angle. When observers turn too far inward, the perceived distance is underestimated as compared to the target (e.g., Figure 1). In contrast, when observers do not turn far enough inward, the perceived distance is *overestimated* as compared to the target. Because these angular errors turn into distances through triangular geometry, overestimation errors are *much* larger than underestimation errors. In addition, if the observer does not turn far enough, the triangular geometry can also produce a perceived target location that is *behind* the observer. Both errors are illustrated in Figure 6. When the target was at 5.49 meters, two trials resulted in target distances that were tens to hundreds of meters overestimated, and one trial resulted in a perceived target position behind the observer. When the target was at 7.32 meters, all of the perceived location measurements were behind the observer. Clearly, these results are nonsensical.

Direct Walk Method. With the changes to the indoor replication, left and right walks were no longer conducted back-to-back in quick succession. Because walking to the right and then to the left required moving the wall from one side of the room to the other, all of the walks to the right were conducted before all of the walks to the left (or vice versa). This minimized the amount of time it took to collect each observer's data.

Because the right and left walks for each distance were counterbalanced, it was still possible to pair them up, as required by the left-right method. However, there was now a significant time lag between paired trials, which challenges the assumption that the paired left and right judgments were immediately synchronous and measured the same perceptual phenomenon. Therefore, as shown in Figure 7, the *direct walk* method was developed. In this method the perceived location is the intersection of the *turn-stop vector* and the *start-target vector*. For each walk, the *turn-stop vector* is formed by the turn point and the stop point; it is the same vector used in the left-right method. The *start-target vector* is formed from the start point and the target point; this is the path that the observer would create if they walked from the start point directly to the target.

While the target location is calculated from pairs of left and right walks in the left-right method, the direct walk method calculates a perceived target location from each walk. Therefore, the direct walk method is not affected by how the left and right walks are grouped in time. However, the direct walk method still uses triangular geometry, and therefore suffers from the same geometric problems as the left-right method. For example, in Figure 7, for the 7.32 meter distance, two of the left walks resulted in perceived distances that were greatly overestimated, while the remaining left walk resulted in a perceived location behind the start point.

Angular Error Method. Both blind walking and blind triangulation by walking are *perception-action methods*, where an observer's *perception* is determined from their *action*. These types of measures are often used in experimental design because they provide a means of assessing perception that do not rely on stored representations that could be cognitively biased [1, 9]. In blind walking, the action is walking, and so there is a very direct mapping between this action and perceived distance. Although triangulation by walking also involves walking, the action from which perception is measured is the angle of the turn that the observer makes at the turn point. However, as discussed previously, using triangular geometry to map this angle to a perceived location biases the resulting errors, in a non-linear fashion, in the direction of overestimation.

Considering these issues led to the *angular error* method (Figure 8), where the observer's turning angle is directly targeted as the error measure. Here, the angle between the *turn-target vector* and the *turn-stop vector* forms the dependent measure. Figure 8 shows how these angles are formed from the representative walked paths of one observer. An angular error of 0° indicates a veridically perceived target location.

4 Conclusions and Future Work

This conceptual replication takes the procedure originally designed in Fukusima et al. [5] and extends it, expanding its potential use cases and allowing novel forms of AR to be tested and evaluated [11]. Further, this work contributes a more complete understanding of how best to analyze the results from triangulation by walking experiments; the geometric and conceptual problems with the left-right method (particularly in this context) are discussed and evaluated. In contrast, the angular error method was found to have higher perceptual validity, allowing for a metric independent of apparent geometric biases. This extension of Fukusima et al. [5], and the new understanding it cultivates, could allow triangulation by walking to be used in new fields and contexts, and is an example of the power of conceptual replication.

Acknowledgments

The authors acknowledge the contributions of Brady Kruse. This material is based upon work supported by the National Science Foundation, under award IIS-1937565, to J. E. Swan II and Cindy L. Bethel.

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