8-9-2022

X-ray vision at action space distances: depth perception in context

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A Dissertation
Submitted to the Faculty of
Mississippi State University
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
in Computer Science
in the Department of Computer Science and Engineering

Mississippi State, Mississippi

August 2022

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Date of Degree: August 9, 2022

Institution: Mississippi State University

Major Field: Computer Science

Major Professor: J. Edward Swan II

Title of Study: X-ray vision at action space distances: depth perception in context

Pages of Study: 200

Candidate for Degree of Doctor of Philosophy

Accurate and usable x-ray vision has long been a goal in augmented reality (AR) research and development. *X-ray vision*, or the ability to comprehend location and object information when such is viewed through an opaque barrier, would be imminently useful in a variety of contexts, including industrial, disaster reconnaissance, and tactical applications. In order for x-ray vision to be a useful tool for many of these applications, it would need to extend operators' perceptual awareness of the task or environment. The effectiveness with which x-ray vision can do this is of significant research interest and is a determinant of its usefulness in an application context.

In substance, then, it is crucial to evaluate the effectiveness of x-ray vision—how does information presented through x-ray vision compare to real-world information? This approach requires narrowing as x-ray vision suffers from inherent limitations, analogous to viewing an object through a window. In both cases, information is presented beyond the local context, exists past an apparently solid object, and is limited by certain conditions. Further, in both cases, the naturally suggestive use cases occur over *action space distances*. These distances range from 1.5 to 30 meters and represent the area in which observers might contemplate immediate *visually directed actions*. These actions, simple tasks with a visual antecedent, represent action potentials for x-ray vision; in effect, x-ray vision extends an operators' awareness and ability to visualize these actions into a new context.

Thus, this work seeks to answer the question **"Can a real window be replaced with an AR window?"** This evaluation focuses on perceived object location, investigated through a series of experiments using visually directed actions as experimental measures. This approach leverages established methodology to investigate this topic by experimentally analyzing each of several distinct variables on a continuum between real-world depth perception and fully realized x-ray vision. It was found that a real window could not be replaced with an AR window without some loss of depth perception acuity and accuracy. However, no significant difference was found between a target viewed through an opaque wall and a target viewed through a real window.

Key words: augmented reality, x-ray vision, perception, depth cues, depth perception

DEDICATION

To all those who journey with me into the bright unknown.

ACKNOWLEDGEMENTS

This material is based upon work supported by the National Science Foundation, under awards IIS-0713609, IIS-1018413, and IIS-1320909, to J. E. Swan II, and IIS-1937565, to J. E. Swan II and Cindy L. Bethel. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author and do not necessarily reflect the views of the National Science Foundation. This work was conducted at the Spatial Perception and Augmented Reality (SPAAR) Lab at Mississippi State University.

Many thanks to all the folks who helped and participated in this dissertation work! These include Mohammed Safayet Arefin, Zack Garris, Farzana Alam Khan, Brady Kruse, and Sandy Phillips, who supported this work with their time and talents. I would also like to thank Dr. Daniel Carruth and my collaborators at the U.S. Army Engineer Research and Development Center, who supported my academic journey. Finally, I would like to particularly acknowledge the contributions of my committee: Dr. J.E. Swan II (my major professor), Dr. Cindy Bethel, Dr. Jeanine Stefanucci, and Dr. T.J. Jankun-Kelly. Thank you, each and every one, for your guidance and contributions to this research!

I'm also grateful for my friends and family who have walked with me throughout this process; your celebration, prayers, and support mean the world to me! I am inspired by your curiosity, engaged by your heart, and humbled by your presence. Thank you for being in my life and being a part of me everywhere I go.

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ANOVA Analysis of Variance

AR Augmented Reality

CAVE Cave Automatic Virtual Environment

FOV Field of View

HMD Head-Mounted Display

HUD Heads-Up Display

OST Optical See-Through

PRP Psychology Research Pool

ROS Robot Operating System

SA Situation Awareness

SEM Standard Error of the Mean

SLAM Simultaneous Localization and Mapping

VST Video See-Through

XRS X-Ray Vision System

CHAPTER I

INTRODUCTION

In augmented reality (AR), there exists significant potential for applications that are relevant and useful at medium-field distances, ranging from 1.5 to 30 meters [23]. This potential is hindered by issues specific to AR devices, especially those of anomalous depth cues. It is expected that these depth cue mismatches significantly impact perceived object location particularly within x-ray vision; however, the extent of this impact, and its related underlying causes, have been considered relatively little within the research. This impact has also not been fully considered in contrast to the nearest ecologically valid task, viewing an object through a window. This dissertation, then, seeks to evaluate the effectiveness of perceived object location in AR x-ray vision in comparison to an analogous task in the real-world and also to analyze some of the potential underlying causes for any differences between the two.

1.1 Introduction

AR is a display modality where computer-generated graphics are superimposed in front of, and support interactions with, a user's view of the real world in real-time scenarios [4]. The aim of augmenting reality is to provide an unprecedented user experience in applications as diverse as manufacturing and repair, military, healthcare, entertainment, and navigation, among others. Due to the dramatic progress of research [26], the wide range of applications [93, 81] and the advancement of commercial AR devices, the importance of AR has increased rapidly. This increased importance has manifested across a variety of different approaches to AR: mobile handheld AR, stationary CAVE-based systems, video see-through (VST) headsets, optical see-through (OST) headsets, and others. Each of these archetypes has its own strengths and weaknesses and has been the subject of significant research. However, this work will focus on OST AR devices and displays, and these, in particular, face some significant limitations that impact their utility: perceptual processing issues (such as depth cue mismatches), context switching overhead, and inherent device feature limitations (such as reduced field of view or lower refresh rates), among others. These factors can significantly effect operator perception of task and environment variables, particularly with respect to depth, presence, and general awareness. Unsurprisingly, each of these attributes is of central importance to many AR tasks.

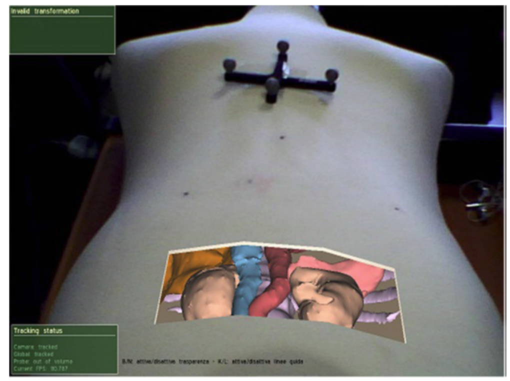
Within the context of AR research, there are a significant number of unsolved problems and unresolved issues. Some of these include broad overarching themes such as how AR devices contribute to user fatigue or how context switching effects AR applications and content, while others are more specific and focused: how can AR best be used to support 3D maintenance instructions? How effectively does a car's AR heads-up display (HUD) improve performance? These topics all represent ongoing areas of interest within the research, but this work focuses specifically on the problem of x-ray vision and depth perception—an application that is actually completely unique to AR!

In AR x-ray vision, operators are able to see beyond opaque surfaces that would normally occlude their view to content presented beyond those surfaces (Figure 1.1). Most typically, this has been envisioned in the form of an operator observing the interior of a room from outside or a surgeon seeing through a patient's skin to the structures or scanned data underneath, but there are a range of other applications in industry, design, and tactical displays, among others. X-ray vision represents an important and unique application for AR head-mounted displays (HMDs), which leads to the natural question of why such an application is not currently under active use and development.

The answer to this is manifold and complex, but a significant factor hindering the adoption of AR x-ray vision is the current limitations of the research, especially as it relates to depth perception, cognition, understanding, and awareness. In order for x-ray vision to be a meaningful construct, it must, at least in some manner improve operators' understanding of the environment. This idea, which in cognitive research is encapsulated in *situation awareness* (SA), is built on three main components: perception, comprehension, and projection (Figure 1.2) [31, 38] . While the idea of SA motivates this work, it is, in effect, focused on the first and most foundational of these components, perception. As a precursor to questions dealing specifically with SA, it is important to quantify and understand the perceptual qualities of x-ray vision.

What perceptual properties, then, are relevant to x-ray vision? While there is a wide field of properties that are likely to feature (including factors such as presence, comfort, or fatigue), an understanding of the displayed environment is by far the most critical in terms of perceptual awareness. While there certainly exists the potential for complicated or busy environments, at its root the problem can be broken down into individual pieces by measuring a participant's understanding of *perceived object location*. This variable, which, in turn, can be broken down into perceived depth and perceived heading or direction, is the essential information that x-ray vision systems must present to operators to significantly extend operator perception [67].

(a) Navigational X-Ray Visualization, 2004 (©2011 IEEE) [6]



(b) Medical X-Ray Visualization, 2019 (Reprinted by permission from International Federation for Medical and Biological Engineering: Springer Nature [25] 2018)

(c) X-Ray Visualization, with saliency-increasing effects, 2009 (©2011 IEEE) [3]

(d) Outdoor X-Ray Navigation, 2011 [27]

Figure 1.1: Various examples of previous x-ray vision research.

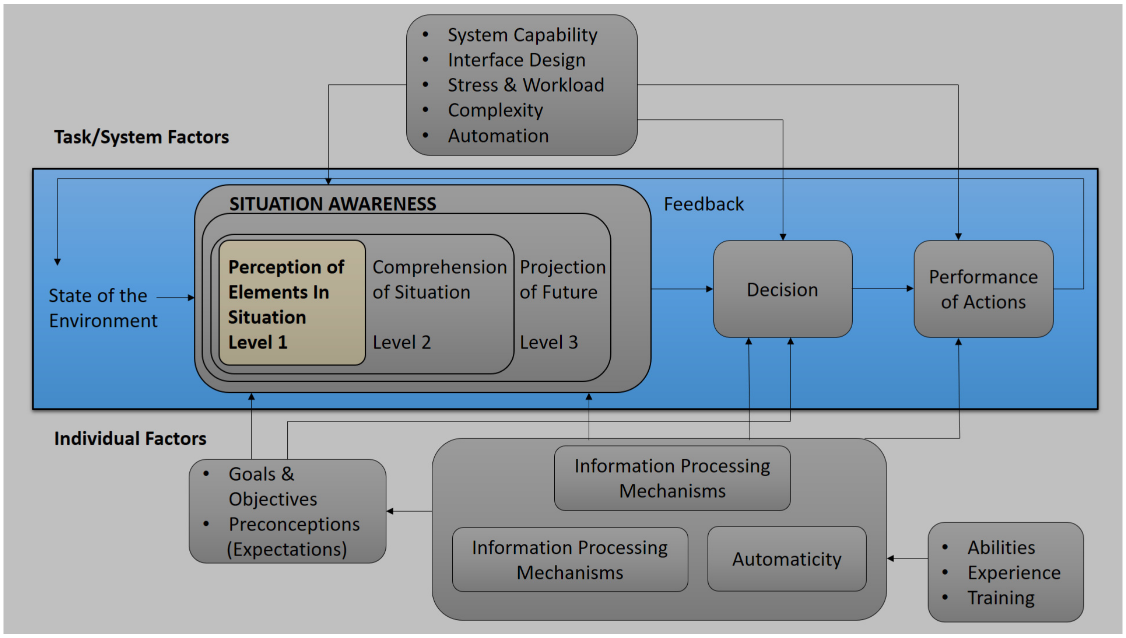


Figure 1.2: A situation awareness model for dynamic decision making [31]

Within the construct of perceived object location, perceived depth is the primary variable of interest. Direction, of course, remains an important variable but in an OST HMD is trivial for an operator to parse with high accuracy. On the other hand, depth information is notably more complicated in AR generally and x-ray vision specifically. Previous research on depth estimations in general OST HMD AR has generally (though not always!) found a pattern of depth misestimation [28, 48, 63, 85, 37, 61], but such quantitative results for x-ray vision research are rare [34]. This is especially concerning as the occlusion inherently present in x-ray vision represents a perceptual contradiction: vision through or beyond an apparently solid object. Such limitations and difficulties in the understanding of x-ray vision hinder its adoption and implementation and keep the benefits of such an application from being readily utilized.

In the study of human depth perception, the specific distances tested are actually quite significant. Depending on the spectrum of distances, different *depth cues* are more or less significant. Depth cues, or the various properties that help humans evaluate the depth of objects, include features such as occlusion, binocular disparity, ground cues, relative size, and many more. As these depth cues vary across contexts, the virtual content from AR or VR headsets becomes more or less effective dependent on the cues used [22, 28]. For x-ray application tasks that require mobility, the most significant distances are *action space distances*, also known as medium-field distances. These distances range from 1.5 to 30 meters and are the distances over which an operator might visualize an immediate intended action [23]. In x-ray vision tasks, then, accurate depth perception at action space distances is paramount to the application's success.

Thus, experimentally developing an understanding of depth perception at action space distances in the context of x-ray vision is of particular importance. In order to develop such an understanding, this work uses a set of tasks known as *visually directed actions* [57]. These are actions which are considered ecologically valid measures of depth perception as they are equivalent to tasks participants might actually perform in the real world. In particular, triangulation by walking is used in this context. As a task that initially involves walking obliquely to the target, it is ideal for x-ray vision; it allows participants to use a visually directed action and walk around the occluding surface. With a wall or other surface in between the participant and the target, a more direct measurement would likely run into (so to speak) perceptual and methodological problems [66, 33, 96].

At this point, the tools to evaluate x-ray vision have been assembled. Tasks can be performed and perceived depth evaluated under this protocol—however, another critical question to consider is how well can x-ray vision be expected to perform? And what attributes of x-ray vision are responsible for this performance? In order to develop a complete understanding of x-ray vision depth perception, it is important to understand the full context of x-ray vision depth perception.

As such, this research investigates a variety of conditions, iterating through a continuum beginning at triangulated walking at action space distances in the real world and ending at full-fledged x-ray vision visualizations and strategies. This approach involves, for initial experiments, conceptually replicating experiments presented in Fukusima et al.'s previous research [33]. From there, the effects of further features, such as environmental context, HMD use, object virtuality, and viewing condition, are examined. In essence, though, the main control condition, and closest analogue to x-ray vision, is real-world vision through a window.

Vision to an object through a window is the closest any strictly real-world activity gets to x-ray vision and represents a likely upper bound on the effectiveness of x-ray vision depth perception judgments. Previous research has generally shown that real-world depth perception at action space distances is very accurate [92, 66, 98, 67, 96], while depth perception to targets perceived through AR is generally less so [47, 90, 63, 85, 37, 61, 34]. X-ray vision applications are expected to follow this trend, though likely with more extreme misestimations, due to the negative effect of the occlusion factor.

As such, it is the goal of this work to investigate x-ray vision depth perception at medium field distances and to evaluate its effectiveness in concrete, grounded terms. This is done through triangulated walking depth judgments, across four experiments. The first experiment conceptually replicates previous work in an outdoor environment, while the second experiment performs a similar experiment indoors and at shorter distances. The third experiment uses the same experimental methodology to investigate the effects of HMD usage, viewing an object through a window, and object virtuality, and the fourth evaluates the effect of three different viewing conditions: real window, virtual window, and opaque wall conditions. This experimental approach will provide data about the effectiveness of x-ray vision depth perception and the various attributes that contribute to or detract from its effectiveness and, ultimately, will answer the main research question (MRQ): **"Can a real window be replaced with an AR window?"** The hypothesis is that a real window could not be replaced with an AR window without some loss of depth perception acuity and accuracy.

1.2 Testing Paradigm

In order to evaluate the main research question, **"Can a real window be replaced with an AR window?"**, it is important to develop a well-defined investigative paradigm. This testing paradigm involves using a visually directed action, triangulated walking (Figure 1.3), to evaluate the perceived object location of targets positioned beyond a window or solid occluding surface in order to directly compare real-world perceived location with x-ray vision perceived location. Building up to the exploratory portions of this research, conceptual replication studies are also conducted on prior experimentation with triangulated walking, in order to verify the experimental methodology and environment for this research and provide further support and credence for the results.

This question targets a hitherto unexamined research area: that of judging the location of objects presented through a window by means of a visually directed action. It is expected that judging a target's location through a wall will introduce a biasing effect; after all, if action factors [39, 2, 83], the shape of the visual field [56], environment [63], nearby occluding surfaces [89], gaps [86] or differing environmental textures [86, 2, 97] can induce differences in depth perception and estimation, it should be expected that a wall might very well also. It is worth mentioning,

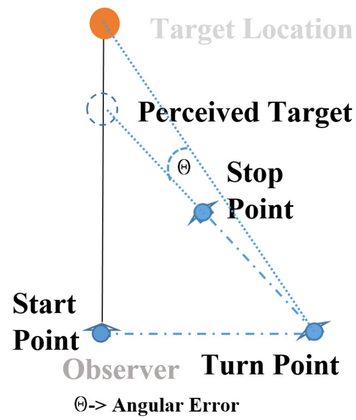


Figure 1.3: Triangulation by walking. In this visually directed action task, participants observe the target, walk without vision to the turn point, then turn and walk toward the target until instructed to halt at the stop point.

though, that it is possible that the presence of the wall might effect visually directed actions differently than cognitive tasks such as verbal report. Indeed, Witt et al. [97] and Andre and Rogers [2] found that different testing strategies (visually directed actions vs. verbal report) could cause participants to switch between action-based and cognitive pipelines without even being aware of a change, resulting in distinctly different depth estimations. It is possible that a similar effect exists for affordances related to walls—after all, it seems reasonable to expect that these action factors might selectively bias only depth judgments relating to the actions they represent [39, 2, 97, 83].

Beyond the above contribution, this research also investigates the current potential of medium field x-ray vision in a categorical way. Not only is this study one of the few that evaluates x-ray vision depth perception [34], but it also breaks down x-ray vision into specific component parts: evaluating participant judgments to targets in an open, outdoors area; evaluating participant judgments in a smaller, enclosed environment; evaluating participant judgments to real or virtual objects seen through a window; and evaluating participant judgments through a variety of viewing conditions, including an opaque wall, a real window, and a virtual window. Each step along this pathway is expected to add additional error to participant judgments, but, prior to this work, the amounts of error each step would contribute was unclear. This research is, as far as can be determined, the first study that compares x-ray vision to comparable analogues in the real world and with non-occluded judgments to virtual targets. Even further, an additional visualization, the *window metaphor*, is evaluated alongside fully occluded x-ray vision. It is likely, based on previous research, that the window metaphor will increase depth perception accuracy [9, 65, 34].

1.3 Research Questions and Hypotheses

This brings us to the main research question (**"Can a real window be replaced with an AR window?"**) and the corresponding main hypothesis. This hypothesis is that a real window can not be replaced with an AR window without some loss of perceptual acuity and accuracy. This deterioration in effective depth perception is important to application tasks and so should be quantified and analyzed, with the effect of each corresponding variable evaluated.

In order to appropriately answer the main research question and evaluate the hypothesis, it is important to address several separate topics. For one, a suitable understanding of the primary variable of concern, perceived object location, is critical to successfully designing a series of experiments to answer the research question. In the research, perceived location has been evaluated based on two components: depth and direction [67]. For all of these experiments (and, indeed, for x-ray vision generally), the second component is trivial; on observing a target, participants will not have trouble identifying the direction of the target whether it is presented virtually or in the real world. The visual stimuli is immediately enough to establish a direction. In contrast, the depth of the object is of more significant research interest, as that has been shown to vary with virtuality, environment, presented depth cues, and many other variables.

As such, though methods presented here test both the perceived direction and depth of presented objects, the primary focus within this research is perceived depth. This variable is a central part of user judgments within the experimental paradigm and, in conjunction with direction, serves as an easily discriminable indicator of perceived object location.

In addition, to answer the main research question, it is important to formulate and answer several smaller research questions (Table 1.1). These move from verifying and conceptually replicating previous research on depth perception procedure and protocols (RQ1, RQ2.1, and RQ 2.2) to measuring entirely novel formulations relating to the perceived location of real and virtual objects beyond a real or virtual window (RQ3, RQ4.1, and RQ4.2). In particular, these latter research questions focus on the role of *object virtuality* and *viewing condition* on perceived depth.

Table 1.1: Research Questions and Hypotheses

Number	*Research Question*	*Hypothesis*
Main	"Can a real window be replaced with an AR window?"	A real window can not be replaced with an AR window without some loss of perceptual acuity and accuracy.
1	"With what certainty can the triangulation by walking method presented by Fukusima et al. [33] be conceptually replicated?"	The results will agree with those of Fukusima et al. [33] and show veridical depth perception through triangulation by walking tasks in an outdoor environment.
2.1	"With what certainty can the triangulation by walking method presented by Fukusima et al. [33] be conceptually replicated in an indoor environment?"	Results will agree with those of Fukusima et al. [33] and show veridical depth perception through triangulation by walking tasks in an indoor environment.

Continuation of Table 1.1		
Number	*Research Question*	*Hypothesis*
2.2	"To what extent do noise cues influence participants' judgment of object location?"	Noise cues will not have a significant impact on perceived object location.
3	"What is the effect of object virtuality on perceived object location when the target is viewed through a window?"	Object virtuality will have a significant negative effect on perceived object location.
4.1	"What is the effect of a fully opaque wall on perceived object location?"	The presence of the fully opaque wall will have a significant negative effect on perceived object location as compared to the real and virtual window conditions.
4.2	"What is the effect of a virtual window and frame against an opaque wall on perceived object location?"	The virtual window and frame will have a significant negative effect relative to the real window condition.

Returning to the overall question, there are two central components that directly effect the main hypothesis. The main hypothesis is that depth judgments through a virtual window will not be as accurate as depth judgments through a real window. This hypothesis will be tested through a series of statistical tests, as detailed in Chapter 8, and the effect of related variables evaluated as described in Experiments 1 through 4, discussed in Chapter 4 through Chapter 7.

1.4 Summary

Within the context of AR research, x-ray vision represents an important application area. Unfortunately, this application is hampered by device limitations and some of the inherent limits of human perception. These issues could potentially cause errors in perceived object location, particularly in the depth component. For tasks at action distances, such errors could cause significant problems in task execution. Thus, it is important to systematically evaluate the underlying causes of these errors and to understand the effect that they have on perceived object location in AR x-ray vision. These are evaluated through Experiments 1, 2, 3, and 4 and used to answer the main research question, **“Can a real window be replaced with an AR window?”** This is done primarily through a comparison to the closest ecologically valid action: estimating the distance to a target seen through a window in the real world. It is expected that judgments made through a real window will be more accurate than those made through a virtual window.

In order to test the main research question, this dissertation is divided into nine further chapters; Related Works, The X-Ray Vision System, four experiment chapters, Results, Discussion, and Conclusions and Future Work. The Related Works section introduces and discusses previous work in the fields of depth perception and AR, introduces key terminology, and briefly discusses the application context of depth perception and x-ray vision. The X-Ray Vision System section details the design and hardware components of the system used to provide x-ray vision functionality. The experimental sections elaborate on the experimental motivation and procedures. The results section details the results from the experiment sections, and the Discussion section contextualizes the experimental results and their overall interpretation. Finally, the Conclusions and Future Work section discusses the contributions and importance of this research, along with opportunities for further research.

CHAPTER II

RELATED WORKS

The technology that is used to create x-ray vision applications is known as *Augmented reality* (AR). AR, sometimes also known as *mixed reality*, supplements the natural senses by overlaying additional information on top of what is natively sensed [28]. However, this approach does have some limitations and downsides; human attention is limited, and additional informational inputs can quickly surpass that limit [31, 32]. Further, cognitive processing for certain types of information, particularly as it relates to depth, may interact negatively with what can be seen in the real world [65, 34].

2.1 Problem Background

Before diving into the intricacies of perception in augmented reality, it is important to briefly discuss the framing and background of this task. To start with, this research is motivated by the idea of *situation awareness*, which can be understood as a representation of what operators are able to understand about a given environment in real time. While this topic has significant depth, it is important to note that the foundation of good situation awareness starts with appropriate perception (Figure 1.2) [31, 38]. While this can mean different things across varied contexts, it thereby follows that perception underwrites the entire structure of situation awareness. Without appropriate perception, the task environment can not be comprehended and, thus, operators are stymied in their decision-making. The specific details of how perception and perceptual accuracy effect a task vary from context to context, but it is certain that perceptual accuracy plays a significant role in situation awareness and task processing.

This brings us to one of the main focuses of this research: How accurately is the data presented by x-ray vision perceived? In this instance, the environment is perceived through *egocentric depth perception*, or depth judgments made with respect to a self-reference. As an example, if a person were to estimate the distance to an object from across a room, they would be using egocentric perception: measuring the distance between themselves and the object. In contrast, if that person were to observe two objects from across the room and estimate the distance between those, they would be using exocentric perception: measuring the distance between two foreign objects. Research has shown that egocentric depth perception in the real world is highly accurate at distances up to about 30 meters, with some research observing accurate depth judgments for much farther distances [8, 43]; in contrast, exocentric perception has been found to be notably less accurate [70, 71]. Thus, exocentric interventions such as robotic camera views of the environment (Figures 2.1) [94] or even tactical mirrors (Figure 2.2) [44], while simpler than x-ray vision, are not likely to be as perceptually sound in the general case. As such, this research focuses on egocentric depth perception as the more important, and more useful, perceptual channel.

Within the context of egocentric depth perception, this research is focused particularly on perception in the medium field, or Cutting's *action space* [23]. This distance stretches from the boundary of personal space (within arm's reach, or approximately 1.5 m) out to about 30 m. This space, roughly speaking, encompasses the area in which one would normally visualize personally acting upon objects: crossing the room to pick up a tool or opening a door, for example. Within the

Figure 2.1: An example of a robotic through-the-camera control scheme (reproduced under the CC BY-NC-SA 2.5 license)) [94]. Note that presented information is inherently exocentric.

action space context, this research is explicitly aimed at distances of less than 15 m, approximately equivalent to the extent of a normal-sized room.

2.2 Perception and Augmented Reality

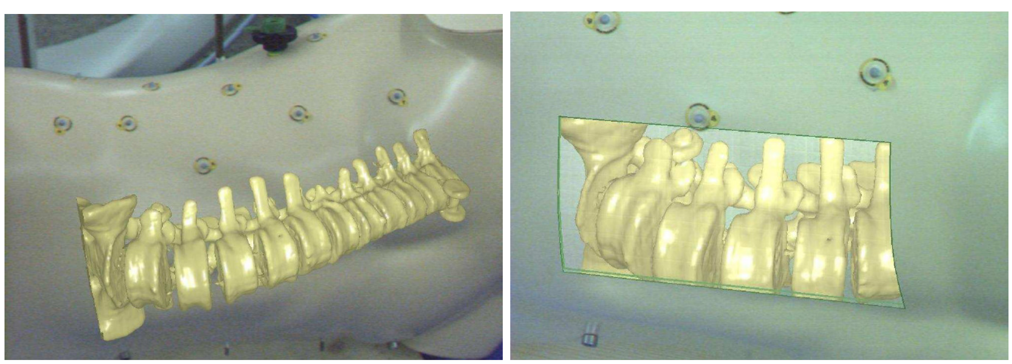
AR x-ray vision, which has been a significant area of interest [6, 35, 53, 64, 65, 3, 5, 61, 25, 27, 34], is a central component of this research. Accurate and accessible augmentation of the environment (Figure 1.1) is a rather important research area, with applications across medical [25], military [35], robotics [19, 15], and manufacturing [61] fields, among others. The x-ray vision task requires the creation of 3D images that appear to occupy specific locations concurrent with the measured position of those objects in the real world, typically behind a wall or some other occluding surface. To provide a sense of distance to these 3D images, *depth cues*, environmental variables used by the human perceptual system to generate a sense of depth, are used. These include occlusion, stereopsis, accommodation, contrast, motion parallax, familiar size, and many more [22, 28].

Figure 2.2: An operator performing mirror reconnaissance. Note that the view the operator sees here is rotated and displaced from his current perspective and is thus exocentric. Photo by ICOR Technology, Inc. [44].

Significant research has been done to determine the relative effectiveness of each of these cues and how they affect augmented reality depth perception [36, 58, 22, 28, 48, 49, 63, 78, 83, 87, 41, 72]; however, a comprehensive approach for accurate depth perception within AR has been an elusive goal [28, 48, 63].

This problem is further complicated by the limited nature of most AR displays. While displays have improved dramatically over the last decade, they are still fundamentally more constrained than natural vision. Indeed, findings in VR research suggest that aspects of VR HMDs have historically biased human perception, with factors such as FOV, weight, and resolution having significant impacts on perceived depth [51, 21, 52, 14]. Few or no commercially available AR displays allow the adjustment of each depth perception parameter [78]. Thus, parameters like multi-focal accommodation, which are relatively difficult to design into mobile display technology, are often unavailable [54, 62]. Other parameters, such as luminance, can generally be adjusted, but current hardware limits fall short of the brightness of a typical sunny day [91]. Fortunately, this particular application is able to offset these shortcomings with several other important depth perception cues, including stereopsis and motion parallax.

Stereopsis, or the combination of stereo images in human eyes to create a sense of depth, has been found to have a strong effect on depth perception within arm's reach [22, 23, 45, 49]. Beyond that, however, the effectiveness of this depth cue deteriorates with distance, though it remains a significant depth cue in parts of the medium field [22, 23, 45]. Even so, on its own, stereopsis would likely represent a potentially fallible depth cue for this application [74, 84]. Fortunately, it is also paired with motion parallax, which has been found in several studies to notably increase depth estimation accuracy [11, 12, 84]. Motion parallax is the sense of depth that comes from observer or object motion, based on the integration of object displacement and perceived motion, and is an important depth cue even in real-world environments. Other depth cues, such as familiar size, contrast, or texture, may have an impact on depth perception [68, 72], but these cues, excepting only occlusion, are notably less significant than stereopsis and motion parallax.



(a) Windowless View (b) Windowed View

Figure 2.3: Example of the window metaphor (Reprinted by permission from Springer-Verlag Berlin Heidelberg: Springer Nature [9] 2007). The first image provides a complete view of the stimuli, but occlusion interferes with perceived depth, causing the image to 'pop' forward in perceived depth. In the second image, the window metaphor clarifies the depth of the image, at the cost of only revealing a limited section of the stimuli.

In a vacuum, it might be expected that stereopsis and motion parallax would be generally sufficient for locating objects in depth [74, 84, 23]. However, there is a complication: *occlusion*, in which an object in front blocks the view of an object behind, is one of the most salient visual cues for human vision [22, 50]. In this x-ray vision task, where occlusion is necessarily ignored, there is a significant perceptual conflict between seeing an opaque wall and perceiving virtual information and objects beyond it (Figure 2.3a). In some cases, this can cause the depth of the virtual data to be perturbed, particularly when it is near the opaque surface [9, 65, 34, 29]. In order to reduce the effect of this perceptual conflict, the *window metaphor* (Figure 2.3b), sometimes also referred to as a cutaway view, is used. The window metaphor and other similar visualizations such as cutaways are methods for contextualizing the display of data past an apparently solid object or even defining a position between two visible solid objects [9, 6, 34]. Generally, humans have no experience with or grasp of seeing a collection of images through an opaque object. However, the context of a window, a bounded frame that lets us see beyond some barrier, is understood. Where a boundary-less mass of floating stimuli beyond a wall might be confusing and bewildering (Figures 2.3a and 2.4), a neat, bounded window through a wall could be expected to be more perceptually understandable and approachable (Figure 2.3b). Indeed, research on this window metaphor or similar concepts has generally found improvement in depth perception estimations, though further research should be done to confirm this phenomenon [9, 65, 34]. Thus, it is expected that the window metaphor will increase user understanding of depth by clarifying the relationship between the occluding surface and any presented virtual objects.

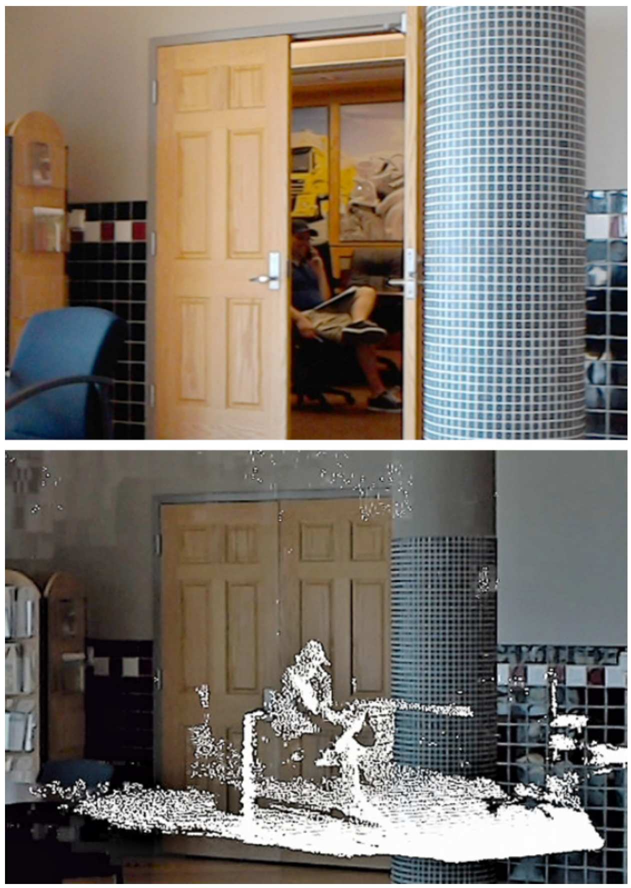


Figure 2.4: An example of a noisy point cloud. Note the boundaryless data and the difficultly localizing the point cloud's position. Image by Christopher Hudson.

2.3 Depth Perception in the Medium Field

For this research, depth perception in the medium field, or action space, is of particular interest. Action space distances encompass the space in which an observer might typically interact with their environment: walking across the room to a chair, talking with another person, tossing an object, etc. [23]. These distances are also notable in that certain depth cues are more discriminable; binocular disparity, accommodation (the depth cue associated with clear retinal focus), and vergence (the depth cue generated by the rotation of the eyes as a component of focus) are all notably less effective in the medium field, while height in the visual field and relative size are correspondingly more central [24]. Motion parallax cue effectiveness varies somewhat within medium-field distances, with it being more effective at nearer distances and less so at farther distances. This background is important, as many of the studies referenced below focus on depth perception for a particular depth cue or combination of cues.

2.3.1 Real-World Depth Perception in the Medium Field

Within depth perception research, real-world depth perception in the medium field has been studied fairly extensively. Research findings have shown that real-world depth perception tends to be highly accurate at medium field distances [92, 66, 98, 67, 96], but that there are many ways to distort or modify that perception [86, 98, 83, 92, 56, 67, 96]. As these studies show, the experimental approaches used to measure depth perception are significant and almost could form a separate research area of their own.

It is important to mention a crucial aspect of the research: human depth perception can not be directly measured, as it is an aspect of a person's experience and not a physical phenomenon.

As such, all the measures used in the research are indirect measures of perceived location (which, in turn, can be broken down into perceived direction and perceived depth) [67]. It is commonly accepted that such indirect methods, detailed further below, reflect a user's inherent understanding of depth; without this understanding, the study of perceived location and depth would be largely theoretical.

Most commonly, human depth perception has been evaluated using *visually directed actions* [57]. These are actions which inherently correspond to a participant's intrinsic understanding of depth and are understood to be very similar to how creatures process and use depth in natural environments. As such, these are generally considered to be the most ecologically valid of perception measures. Visually directed actions include such tasks as walking to a target [66, 92, 86, 98, 83, 2, 96], triangulation by walking or pointing [66, 33, 96], throwing a beanbag [83], turning in place [83], or reaching for an item [88], among many others.

In depth perception research, the most common visually directed task used for depth perception is blind walking, which has been found to be an accurate measure of perceived distance as estimates made using full-cue blind walking tend to be veridical with respect to the real world [66, 92, 86, 98, 83, 2, 96]. In this task, a participant observes a target for a certain length of time. Then, the participant either closes their eyes, is blindfolded, or the target is otherwise hidden from their view before they are asked to make a direct walk to the target. The distance the participant walks is measured, and the result is considered as the judged depth of the experimental task. Triangulation by walking (Figure 1.3) or pointing is quite similar to blind walking; however, instead of walking directly to the target, participants walk obliquely a certain distance before then turning and walking or pointing toward the target. Some variations of this approach have participants continually point toward the target as they walk obliquely to it. The last three visually directed actions are fairly self-explanatory: for bean bag tossing, participants view a target, then close their eyes and toss a beanbag toward where they think the target is; for turning in place, participants view a target, then close their eyes and attempt to rotate 360° to turn back around and face the target's original position; and for blind reach, participants reach toward a previously seen target with their eyes closed. There are many other visually directed action tasks, but these serve as a short summary of what can be expected in that area.

There are a variety of other perceptual measures that don't correlate directly to motor movements; unlike visually directed tasks, these are thought to involve more cognitive processing, as opposed to using a visually directed pipeline [2]. Chief among these is perceptual matching, which encompasses a large number of experimental protocols all based on matching some characteristic related to a target's depth with a proxy object under the participant's control [66, 92, 86, 84, 89, 98, 56]. Sometimes this control occurs through the manual manipulation of an object; other times the object is manipulated through a remote control or verbal command. Some perceptual matching tasks involve matching the distance to the target with the distance to the proxy object; others involve positioning the proxy object at the midpoint between participant and target; and still others involve adjusting the apparent depth of the proxy object through a stereoscope. Verbal report is also used as a depth perception measure [2, 97, 80, 84]. In this task, participants view a target and then verbally report how far away it appears to be. It is a common task in the depth perception literature, though its association with cognitive factors keeps it from being used more freely [84, 2]. Finally, there is one last category of depth perception tasks: bespoke depth measures. These measures are very focused, often used only in very specific contexts or to measure specific depth cues and exclude all others. These might include relative depth orderings, estimating the movement of an object or light, and other highly specific tasks [42, 49].

Each of the tasks detailed above has its own strengths and weaknesses as a measure of perceived location. Each of these tasks has been used in the research; however, there seems to be some evidence that different types of tasks produce differing estimates of depth. For example, Andre and Rogers [2] postulated that differing experimental tasks used separate perceptual pathways, in particular comparing verbal reports with blind walking in the medium field. They found that blind walking was generally accurate out to about 30 m, while verbal report was significantly less accurate at those distances. Further, they tested two different environment types and found that the environment type (outdoor and unconstrained/flat vs. indoors and limited/cluttered) significantly effected the verbal report depth estimations, but not the blind walking depth estimates. Andre and Rogers also found that the application of base-up and base-down prisms could be used to alter blind walking distances while leaving verbal report judgments unaffected. Rieser and Pick [83], in their landmark study, also found that calibration and the effects of optical flow (the apparent motion with which an observer moves relative to their environment) have a significant effect on human depth perception in the medium field, dependent on task type. When performing an activity (either walking, turning, or throwing) on a treadmill that is being towed at a certain speed (Figure 2.5), participants calibrated the action they were performing, incorporating the additional optical flow or target drift (the effect, in the throwing condition, of tossing judgments being modified by the towing speed), depending on the activity. Between experimental pre- and post-tests, Rieser and Pick found that participants' walking, turning, or throwing judgments changed if that action had been performed on the moving treadmill–but that the calibration of the other actions appeared to be unaffected. They also identified height off the ground as a significant component of the calibration seen in their experiments.

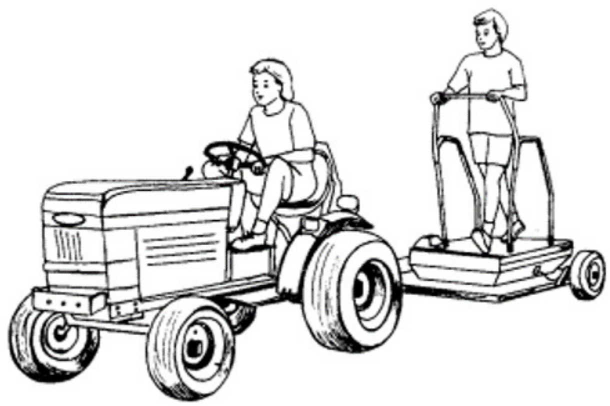


Figure 1. Drawing of the treadmill towed behind a tractor on a *low trailer. It was used to induce change in the calibration of* forward walking.

Figure 2.5: An illustration of the experimental setup of Rieser and Pick (Copyright 1995 by American Psychological Association. Reproduced with permission.) [83]. A participant is towed by a tractor while walking on a treadmill, inducing additional optical flow in the participant. This optical flow is associated with temporary depth misestimations when the participant performs blind walking judgments to targets without the extra induced optical flow.

Related to this work, Gibson [40] developed the concept of affordances–that is, in depth perception research, the idea that humans view aspects of objects or the environment with respect to their action potential. When viewed in the context of walking, a spot on the ground affords support or stability; when viewed in the context of throwing, a beanbag supports tossing. This relatively simple construct has a lot of meaning and importance for depth perception. As in Rieser and Pick's study [83], this suggests the idea that independent actions, or affordances, are calibrated individually in human depth perception. It also suggests that these affordances can be used to modify depth perception in sometimes surprising ways. In Linkenauger et al. [59], the handle direction of a tool modified the perceived distance to the tool for right-handed participants in near-field depth perception. Left-handed participants were unaffected by this intervention, perhaps due to frequently interacting with tools aligned for the right hand.

This approach was also expanded upon by Proffitt et al. [80], who postulated that perceived egocentric depth in the medium field is influenced by the perceived effort of a given task. In their research, subjects participated in one of two conditions: wearing a backpack (with about a fifth or a sixth of the participant's weight) or not. During the experiment, participants made a verbal report to a target that ranged from one to 17 meters away. The participants wearing the heavy backpacks reported farther distances than the unencumbered participants. This research also investigated modifying the optical flow, using treadmills, to induce an expectation of increased effort in participants. Under this expectation, participants evaluated distances as farther away, further supporting the idea that distance perception through visually directed actions can be modified by the expected effort of the action. Witt et al. [97] also researched effort and its effect on depth perception tasks in the medium field and found that the perceived effort of an intended action modified the depth associated with that action and with other measures influenced by cognition, but did not effect the depth estimated through an independent visually directed action or task. More specifically, subjects participated in several experiments where they threw a ball at a target located four to 10 meters away. The participants received either a light ball to toss or a heavier ball to toss. In both conditions, participants threw the ball with the same accuracy, but participants with the heavier ball verbally reported that the target was farther away. Participants with the heavier ball reported the target as farther away using a perceptual matching task as well. However, with the same approach, participants accurately judged the distance of the target during the tossing task in both the heavy and light ball conditions. Finally, in the last experiment of Witt et al., the researchers modified the intentions of the participants; one group performed the throwing task and expected to throw to the target, while another group expected to walk to the target. In this case, the verbal reports of the throwing group were overestimated, while the verbal reports of the group that intended to walk were estimated accurately. These experiments mutually reinforce the idea that there are meaningfully different ways to measure perception–and that it is important to carefully consider the nature of the experimental tasks.

Further relevant to this theme, Lappin et al. [56] found that the structure of the visual field is significant when making depth judgments in the medium field using a bisection perceptual matching task (a task where participants indicate the perceived distance between themselves and a target by positioning an object at the perceived halfway point). These researchers tested three environments: a hall, a lobby, and an outdoor, grassy field. They found significant, repeatable differences in perceived depth at each of these three locations. The specific reasons why this effect was observed are not clear, but it seems to be related to environmental context and structure. Similarly, Witt et al. [98] also found that the structure of the environment could modify depth perception in the medium field, dependent on the perceptual task. These researchers evaluated two environments with natural obstructions: the end of a hall and a field with an edge boundary. They also found that in a bisection perceptual matching task, targets positioned near the boundary or wall seemed farther away than targets in a more open section. In contrast, however, they found that, for standard blind walking tasks, there was no significant difference for targets nearer to environmental boundaries. For blind walking tasks where participants were instructed to walk an equivalent distance in the opposite direction, an effect of the environmental obstructions was again found. This seems to indicate that, when considering the target in terms of distance, environmental obstructions modify that; when considering directly walking to a target, the effect of environment appears to be diminished. With this research, it seems clear that the relationship between depth perception, environment, and task is important and that these variables interact in often unexpected ways.

Even beyond this, the state of the participant is an important component of depth perception. In Proffitt's research on embodied perception in the medium field [79], he discusses the impact of fear, effort, affordances, social influences, and other factors on the perceived depth of objects in the real world. Each of these influences has been shown to have a significant effect on perceived depth and can modify participants' depth judgments.

Past these broader concepts within depth perception research, there are many studies in the medium field focused on traditional depth cues and associated discussion. Gogel et al. [42] found that motion parallax, without other depth cues, was notably fallible. Using a setup that eliminated other cues and that tested binocular and monocular conditions, the researchers found that human depth perception tended toward a 2 meter distance unless acted upon by another cue or source of information. In that context, the motion parallax cue, instead of modifying perceived depth, presents as a perception of motion to human observers. In contrast to this research, Rogers and Graham [84] found that motion parallax could singly inform an absolute depth estimation. They tested this by using random dot stereograms in order to simulate motion parallax. Their findings indicate that both user-generated motion and external motion can generate a perception of depth, but that user-generated motion is generally more effective.

Thompson et al. [92] found that the lack of ground cues, in an otherwise full-cue setting, do not of necessity reduce the accuracy of depth estimations in the medium field. In their research, participants used an open-loop visually directed task (blind walking) and an open loop matching task (adjusting the position of a pointer on the floor to match the target distance) to estimate the position of targets placed on the ceiling rather than on the ground. Depth estimations were found to be equivalent to those of targets viewed on the ground in the blind walking condition, though the matching protocol revealed depth overestimation for the ceiling targets. Sinai et al. [86] , in contrast, found that estimated target depth could be perturbed by the introduction of a gap, texture change, or drop between the participant and the target. Their findings were that, in a full-cue level environment, participants accurately judged the distances to targets from 3.7 m to 8 m, across both blind walking and perceptual matching tasks. When the distance to the target was across a gap .5 m deep, participants significantly overestimated the position of the target across both tasks. For both tasks, participants also overestimated the horizontal distance to targets positioned below and in front of them. Finally, distance was underestimated when walking across a ground plane with different textures (grass vs. concrete). This research shows that ground plane cues are somewhat complex–and that their presence can inhibit as well as aid accurate depth perception to targets in the medium field.

Loomis et al. [66] tested two different visually directed action techniques and found them both accurate for medium field distances. The techniques tested include blind walking and walking obliquely while pointing. In the second technique, participants viewed a target and then were instructed to close their eyes and walk obliquely to it, while pointing at where they believed the target to be. Loomis et al. also found that, while judgments to targets on the frontal plane were highly accurate, estimations involving the sagittal (or left/right) plane were significantly less so.

2.3.2 Augmented Reality Depth Perception in the Medium Field

Swan et al. [89] found that depth judgments to modified AR targets in the medium field were highly accurate. In their experiments, participants controlled a virtual target and were instructed to match it to a physical target, either on the ceiling or on the ground. This target exhibited an extra depth cue–for nearer distances, it was highly visible and luminous; for farther distances, it appeared transparent and faded. For certain trials, the view of the environment was bisected vertically by an occluder (the position of which, top or bottom, was randomized), but the portion of the view containing the depth targets was not obstructed. The presence of the partial occluder was found to increase measured error, and occluder position, target location (ceiling/floor), and target distance were all found to have significant effects on depth perception. This experiment was extended in Swan et al. [90], which investigated depth judgments to targets at three, five, and seven meters through blind walking and verbal report trials. They particularly investigated the effects of wearing an HMD while viewing a real-world target and viewing a real-world and virtual target concurrently in the same position. General findings were that distances in AR were observed to be significantly underestimated; the physical effect of the HMD was evaluated as contributing significantly to that underestimation. This finding of the significance of the HMD was confirmed in Jones et al. [47]. Through a series of four experiments, they discovered the significance of optical flow as an indirect training and feedback method in AR–participants who performed blind walking trials learned from the optical flow that crept in and performed better on future tasks. Jones et al. also found a general underestimation of perceived egocentric distance at about 76% of actual distance. Of further significance, they found that judgments to real targets made through an HMD were not significantly different from judgments made to virtual targets, suggesting the primacy of the HMD's contribution to the observed underestimation of distance.

Rosales et al. [85] evaluated AR medium-field depth judgments to targets presented on the ground and floating off the ground through blind walking evaluations. They found that depth judgments for all targets were underestimated and that targets presented off the ground were seen as farther away. This effect was more profound for monocular viewing than it was for binocular viewing. It is possible that this effect is caused by participants viewing the objects as presented on the ground but farther away.

Gagnon et al. [37] also evaluated medium-field depth judgments in AR. In their tasks, participants viewed a target person in AR or in the real world and then adjusted the position of a real person standing obliquely to the target axis. Participants were instructed to verbally instruct this person to move forward or backward until they matched the distance from the participant to the target. In experiment 1, this task was performed in a large, open room and in a more constrained hallway. It was found that environment type had a significant effect in both the real and AR conditions and that the AR condition was underestimated in comparison to the real world and to actual target distances. In experiment 2, participants verbally reported the distances to the target; it was found that distance underestimation in AR persisted for this task (and even was of a greater magnitude!). Distance was also underestimated in the real world for this task, and learning effects were reported in the real-world condition, though not in the AR condition.

Livingston et al. [63] found that depth judgments to AR targets in the medium field were underestimated in an indoor condition and overestimated in an outdoor condition. This research involved a perceptual matching task where participants were required to match the position of a physical object with the position of a movable virtual object under their control. A novel calibration scheme was deployed for this research as well.

Liu and Siepel [61] studied depth judgments to occluded and displaced pipe targets in AR. This research is somewhat more complex than traditional depth judgment exercises as participants viewed each displaced pipe through a solid wall and were instructed to select the wall location that was closest to the pipe's position, at a location oblique to the participant's viewing direction. Liu and Siepel's findings were that pipe position judgment in a full-cue environment was more accurate than would be expected for participants who were not evaluating the pipe's position based on motion parallax. They also found that pipe position was not estimated with complete accuracy, suggesting that the occlusion cue, object virtuality, incomplete processing of motion parallax, or some other potential issues were preventing accurate object position estimation.

2.4 Depth Perception Accuracy in an Application Context

Before diving into the question of how to measure the effect of x-ray vision on spatial perception, it is helpful to further discuss the relationship between depth perception and task performance. Not all tasks will have a need for highly accurate perceptual judgments; trivially, HUDs and other text-based interfaces don't typically require depth estimations at all.

On the other hand, accurate depth placement is extremely important in the use of x-ray vision for particular applications, such as guided surgery. In this context, a doctor would be performing a medical operation on a patient—say, removing a tumor, carefully positioning a probe or scalpel, or understanding the position of a patient's organs—and would need high-accuracy location information to perform this operation. This information could have been gathered in the form of a medical scan and might be visualized in augmented reality. Here, it is clear that depth perception fidelity is an extremely important component of the doctor's task effectiveness. Without this knowledge, the doctor's understanding of the relevant parts of the environment decreases, and the task becomes more complex, difficult, and prone to failure. Thus, in this context, accurate depth perception matters.

While this example does help clarify a potential role for the importance of depth perception, there are still a lot of differences between a near-field surgery application and applications that are more likely to utilize medium-field distances [24]. What role can depth perception play in some of these applications? The answer here is a little more ambiguous—after all, there are not many medium-field applications where a centimeter difference in depth perception is as important as it is in guided surgery. However, particularly in dangerous environments, sometimes a high level of depth accuracy is important—imagine how crucial a potential error of just 10% might be! This error is somewhat on the low end of what has been observed in VR depth perception [82], and AR depth perception has found variable results [28, 48, 63]. In extant data on x-ray vision depth perception, from Furmanski et al. [34], participants routinely misestimated the position of an occluded object by a meter or more. This data likely would differ significantly from direct measurements from a current x-ray vision system, largely because of the experiment's forced-choice selection, requiring participants to select from one of three relative distance options. This could act to artificially lower (or, potentially, inflate) user depth errors to the virtual target. Further, the data is monocular in nature and from an era with significantly heavier and less powerful AR devices, and does not specify the actual distance from the participant to the target. Even so, consider the effect one meter of error might have during an active shooter incident or a hostage situation. In such a situation, adrenaline and stress typically run high, and fractions of a second are extremely significant, in consideration of standard human response times. A meter error in depth accuracy might represent a valuable second or half-second during which the situation could rapidly deteriorate.

Even beyond such serious situations, there are other examples where accurate medium-field depth perception is important. Consider the case where there is a smoke- or steam-filled environment. Without some other specialized equipment, it would normally be impossible to understand or safely navigate such an environment. With an application similar to the x-ray vision system, it would become possible to navigate and understand that environment—either with a robotic proxy or personally, equipped with an AR device displaying the environmental depth data. If depth data were misestimated by a meter or more in this situation, it would become more difficult to evaluate or appropriately plan paths around distant obstacles. As another example, consider an operator remotely navigating a hostile environment with a robotic platform. This robot could be equipped with a number of features such as articulated grabber extensions or manipulator arms. To naturally move and interact with the environment, depth information would be useful and important; not only would robot movements be easier to more accurately plan, but also robot affordances and actions could be more readily understood and used. In many robotic teleoperation systems, depth data and cues are unclear or ambiguous, notably increasing the complexity of tasks such as accurately manipulating a grabber arm to a desired location or navigating a robot through a complicated environment [94, 15]. In instances where time is an important variable (such as disaster response) or where only one attempt can be made (such as avoiding getting stuck in a tunnel or falling off a ledge), the improved speed and accuracy of egocentric depth judgments can prove critically important.

There may also exist some more general tasks where precise depth judgments aren't strictly important: say, an industrial application for observing the contents of cargo containers or pipe installations beneath the ground [61]. For these tasks, highly accurate depth perception likely isn't critical; misestimations of around a meter may not negatively effect task performance significantly. However, if misestimations are large in magnitude, perhaps on the order of 50% or more, it is somewhat difficult to imagine x-ray vision contributing usefully even to the most forgiving of depth tasks.

For these tasks, then, the performance generally observed in standard, non-occluded AR would be sufficient [82]; however, if the occlusive effect of x-ray vision is strong enough, it seems reasonable to expect a correspondingly larger error in depth judgments. The application of the window metaphor should help to reduce the observed error in x-ray vision, and it seems unlikely that the resulting depth error would be large enough to disrupt non-demanding applications; however, gross depth misestimations could potentially be significant, even in fairly lenient environments and contexts.

Accurate depth perception is important for a significant number of different task environments. The range of accuracy needed may vary, but many AR applications require some degree of user depth understanding to successfully function. Improved depth perception may also have some bleedover effects, such as improved presence, which could increase the realism and usability of the application [60]. In sum, depth perception matters and is central to the main theme of whether a real-world window can be replaced with a virtual window.

2.5 Summary

Depth perception in humans is based on a complex patchwork of visual cues that interact one with another. These cues, when not representative, can provide information that disrupts accurate depth perception. The full measure of how visual perception works is even now not fully understood—and this is especially true of visual perception in AR. Researchers in AR have come to a number of different conclusions with respect to depth perception in AR, dependent on task, environment type, and many other variables. More particularly, x-ray vision depth perception has been rarely experimentally evaluated; this is especially relevant due to the conflicting nature of the occlusion cues in x-ray vision. As accurate depth perception in x-ray vision contexts is important in AR applications, this merits further study, as proposed in Chapter 1.

CHAPTER III

THE X-RAY VISION SYSTEM

In order to accomplish this work, an *X-Ray Vision System* (XRS) was created and deployed. This system leverages an AR headset and a fiducial tracker to allow the placement of a virtual window through which room content can be seen and understood. This window and content are presented in augmented reality and so do not exist in the real world but act to provide depth cues to unseen objects. The resulting depth information, both from the window itself and from the depth information beyond, affords a variety of depth cues for interpreting the data.

Discussion of the XRS is split here into two sections: one focusing on a functional testbed application demonstrating functionality and usability and the other focusing on the experimental program.

3.1 General Apparatus

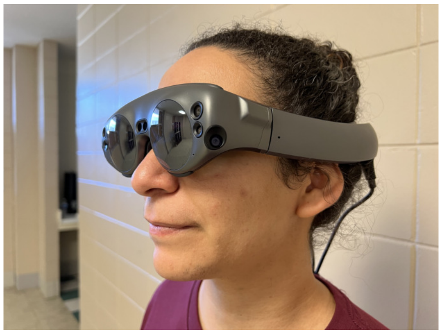
The most important hardware component for this system, in both the experimental and testbed modes, is the AR headset: the Magic Leap One (Figure 3.1). This OST HMD supports a variety of features that are important for this application: accurate simultaneous localization and mapping (SLAM) tracking, fiducial tracking, background wall/floor mapping, a refresh rate (122 Hz) and field of view (40° horizontal, 30° vertical, and 50° diagonal) worthy of a modern AR device, and significant processing power (with an NVIDIA® Parker SOC CPU) for a mobile AR device [13, 1].

This device is worn on an operator's head and allows the operator to see both the real world and overlaid virtual graphics. Other than the headset itself, the device also is tethered to a computing core (called a Lightpack) in order to reduce the weight on an operator's head. This system can easily be clipped to a belt, placed in a pocket, or even carried by hand, if desired.

This system also uses some additional hardware components. In particular, a network connection is used in both contexts. This network does not of necessity have to be connected to the internet, but it is important for sending data to and from the Magic Leap One headset. An Alienware 17 R3 with an NVIDIA® GeForce® GTX 970M with 8GB GDDR5 is used to drive the non-AR side of both applications. This computer is quite powerful, but observation indicates that almost any capable modern system suffices for this task. Lastly, a printout of a tracking fiducial, the design of which was provided by the Magic Leap corporation, is used to calibrate the position of virtual objects in both simulations.

3.2 Functional Testbed

In performing this research, one of the evaluated components was whether an x-ray vision system was feasible in the real world at all. Such a system could be visualized as autonomously or semi-autonomously exploring an unknown environment and relaying depth information to some number of outside observers through augmented reality. As background and support for these experiments, it is important that such a system be both feasible and achievable, and, indeed, an effective x-ray vision prototype was developed for this research. This functional testbed of the system was designed with capabilities that such a system would have in actual practice. The testbed



(a) Magic Leap One AR headset.

(b) Full-body view of the Magic Leap One.

(c) RealSense D435 Depth Camera (Graphic courtesy of Intel Corporation) [20].

Figure 3.1: Main hardware components of the X-Ray Vision System (XRS).

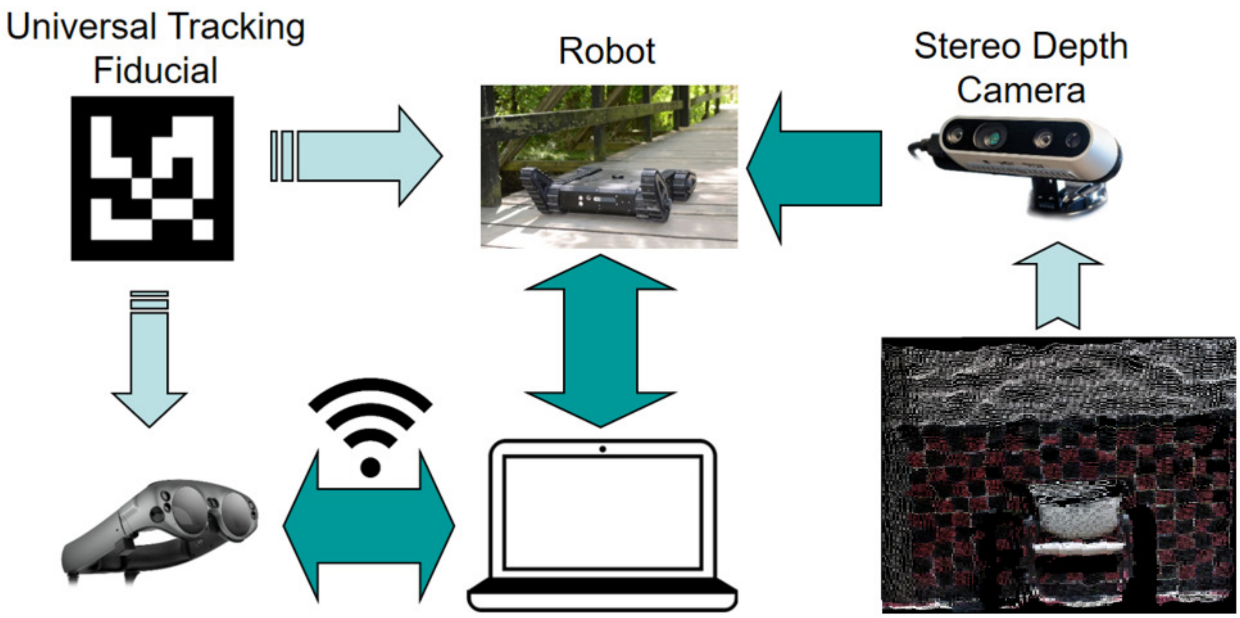


Figure 3.2: A flowchart detailing the interactions between the components of the X-Ray Vision System (XRS) in an envisioned application context [77]. Note that the stereo depth camera and robot were not used in the dissertation experiments described in later sections.

was not used in the dissertation experiments described in later sections, but knowledge from its construction and use informs the motivation and reasoning for this research.

For the functional testbed, the XRS makes use of two additional features: a mobile robotic platform and a stereo depth camera (Figure 3.2). These components expand the functionality of the XRS into application contexts, allowing investigations into x-ray vision as an operator might actually use it.

3.2.1 Testbed Design and Hardware

From a technical point of view, the functional testbed has a simple, straightforward design, with a minimal hardware footprint (Figure 3.2). For a basic demonstration, all that is required is a stereo depth camera with a network interface, a Magic Leap One AR headset, and a fiducial to calibrate the positional offset of both. This, of course, can be expanded to include robotic platforms, a dynamically changing environment, and multiple users; indeed, the system actively supports such a configuration.

The main additional hardware component for the functional testbed is the stereo depth camera: the Intel RealSense D435 (Figure 3.1c) [20]. This camera uses an infrared projector and two imagers to capture 3D room information. It also uses an RGB module to capture color information, as well, further improving the clarity of the visualization. Together, these systems observe, calculate, and transform the room data into a 3D point cloud that can be transferred to, and displayed on, the Magic Leap One AR headset. The range of the device is approximately .11 to 10 meters, and the field of view is roughly 40° horizontal by 30° vertical (for a 50° diagonal field of view) [13]. All told, together this makes for a powerful and adaptable stereo camera—an excellent tool for the functional testbed.

3.2.2 Testbed Operation and Software

In a non-experimental context, the operation of the XRS is reasonably simple, masking a lot of the complexity occurring within the system itself. Before starting, it is important for the Magic Leap One to have a network connection to the system controlling the stereo depth camera (though this does not necessarily need to have internet connectivity). On startup, the participant must move to within a few feet of the tracking fiducial, center it in their view, and press a button to calibrate the coordinate system. At that point, the participant can walk around the environment, placing the x-ray window on any sufficiently sizeable flat surface to view the depth data gathered from the stereo depth camera.

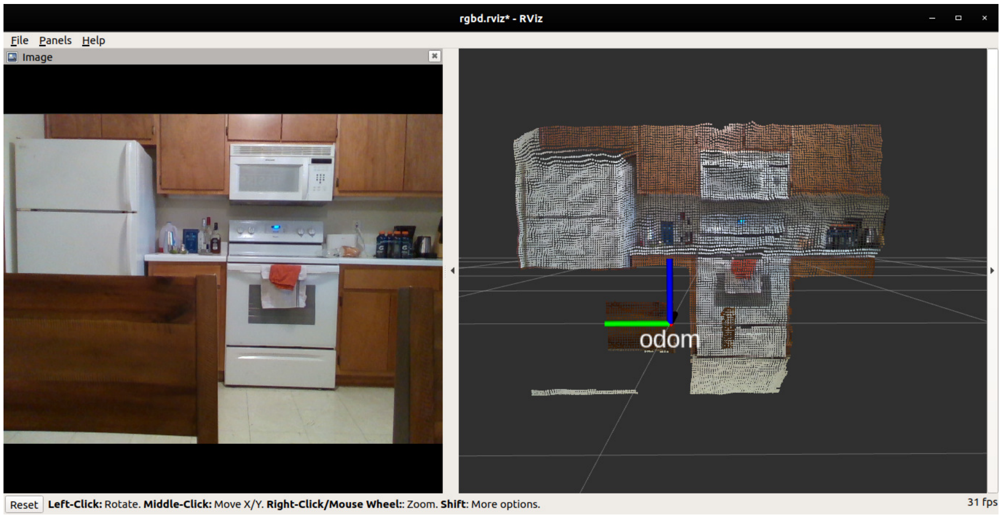


Figure 3.3: A pointcloud of a scanned room in comparison with the original, displayed in the Rviz software [75]

Under the surface, however, there is a lot more going on. After start-up, the Magic Leap One headset's forward camera is actively searching for something matching the design of the selected fiducial. When that surface is recognized, a visual prompt is displayed through the headset, and the calibration can be completed with a button press. After synchronization, remembering the position of the fiducial, and any other scene objects, falls to the Magic Leap One's SLAM algorithm. This builds a local environment map and allows the Leap to keep track of its own position and orientation, as well as the positions of other scene objects. In practice, this tends to be very effective, with consistent virtual object locations over a significant period of time and application use. Beyond that, the Magic Leap One also scans the environment, identifying walls, floors, and ceilings as the operator moves about the environment. In effect, each of these surfaces affords the ability to place the X-ray window. This window can be placed as many times as desired and will be oriented parallel to the flat surface it is placed on. The X-ray window and the stereo depth data both operate on a specific, offset stencil buffer value, ensuring that displayed depth data is only visible through the x-ray window.

In the functional testbed, this depth data is exported from the camera using a software system called Robot Operating System (ROS) in the form of point clouds. These point clouds, exported in a file known as a ROSbag, contain all the scanned depth information from the stereo camera, updated as the environment is explored (Figure 3.3). This allows for the efficient exporting and processing of camera depth data by the AR headset.

In creating and developing the XRS testbed, an iterative process was used to expand out the features in the system. This started with early prototypes that incorporated a pre-recorded object point cloud, a virtual window, and a calibration fiducial (Figure 3.4). With continued development, these expanded into a full-fledged system with features that included improved visualizations and live feed camera data (Figure 3.5). This system allows multiple instanced subscribers, free movement through the environment, and placement of the virtual window on any large, visible surface.

(a) View 1

(b) View 2

Figure 3.4: A prototype of the XRS functional testbed. Note that, viewed egocentrically with stereopsis and motion parallax, the virtual graphics give a strong suggestion of being "really there."

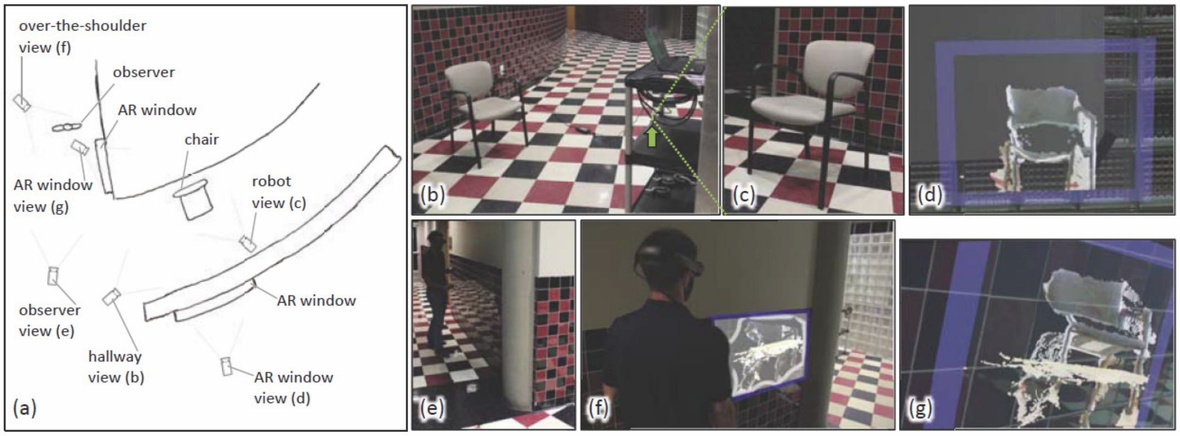


Figure 3.5: Full overview of the *XRS* testbed. A stereoscopic depth camera is oriented toward a chair (b, c), and allows a user around the corner to see the chair through the wall (e, f). Various other AR window positions (d, g) help express the flexibility of this system and show how the position of the chair is communicated through walking and movement.

3.3 Experimental Program

The experimental program is broadly similar to the functional testbed outlined above, but with a notably different approach. In the experimental program, used in Experiment 3 (discussed in Chapter 6; summarized in Table 7.1) and Experiment 4 (Chapter 7; summarized in Table 7.1), the focus is on presenting a single discretized location target per trial. Participants in both experiments provide a location judgment to that target as described in the experimental sections below.

The displayed target is a virtual object that looks like a green cylinder with the dimensions of a 6.7 inch-tall soft drink can. The Magic Leap One headset is still calibrated to a single fiducial that controls virtual object locations, but those locations are now based on pre-recorded room measurements and observation. Each target location was verified and visually compared to a corresponding real target in several pre-experiment calibration sessions.

Past that, the experimental program makes uses of custom input files to automatically switch between distances, conditions, and direction variables (as described in Chapters 6 and 7) without any user input. This allows the experimenter to run the experiment from a laptop without disrupting the participant's experience. These features combine to support a streamlined, error-resistant process for both the participant and the experimenters.

3.4 Summary

The development of, and research into, the x-ray vision system (XRS) has resulted in two distinct approaches. In one, an application environment was created enabling end users to view live stereographic video data from their own displaced perspective. Opportunities for this approach to be functionally extended are plentiful, but the main takeaway for this research is that this technology is usable in live application contexts.

The second pathway that has been developed is an experimental program that allows for the evaluation and analysis of perceived object location by end users. This program evaluates participant judgments to virtual targets under a variety of conditions and distances, as discussed in Experiment 3 (Chapter 6) and Experiment 4 (Chapter 7).

CHAPTER IV

EXPERIMENT 1: TRIANGULATION BY WALKING IN AN OUTDOOR ENVIRONMENT WITHOUT HMD AT ACTION SPACE DISTANCES

Experiment 1 (Table 1.1) was designed to answer Research Question 1 (RQ1), **"With what certainty can the triangulation by walking method presented by Fukusima et al. [33] be conceptually replicated?"** In order to answer this question, a modified version of the triangulation by walking method presented in Fukusima et al. was used to evaluate depth perception to real-world targets.

Hypothesis 1 (H1) was that the results from this experiment will agree with the results from Fukusima et al. [33] and show veridical depth perception through triangulation by walking tasks in an outdoor environment. High certainty in the conceptual replication was further expected, and the results of Experiment 1 were visually compared to the results of Fukusima et al., as their numeric results were not available; these findings can be seen visually in Chapter 8 Figure 8.8.

Task: The purpose of the primary task was to estimate perceived 3D location of objects in an open, outdoor environment at action space distances (Table 4.1). Participants observed a target (a 6.7 inch tall, bright green soft drink can) located six, nine, or 12 meters away across a large parking lot at Mississippi State University (Figure 4.1a). Participants observed this target while facing obliquely away from it, toward an experimenter who walked them through task execution

(a) The overall environment.

(b) A view of the rightward path the participant would walk. The experimenter stood in this spot to demonstrate the initial walking direction. Note the subtle tape marks on the ground (highlighted in the image).

Figure 4.1: The outdoor environment of Experiment 1

(Figure 4.1b). They were instructed to observe the target and fix its location in their mind before closing their eyes and walking toward the experimenter. At a certain point along their walk, they were instructed to stop and turn toward where they believed the target to be. At this juncture, there would be a short pause while the experimenter placed a bean bag directly behind their center of mass, evenly spaced behind their two feet standing still. Participants were then instructed to walk confidently forward for several more steps before being halted again, and having another bean bag placed behind their feet. Participants were then led, with their eyes still closed, back toward their starting point. When they were reasonably close to it, they were instructed to open their eyes and resume standing at the starting point, facing away from the experimental field, until the next task was ready. During this brief intermission, the experimenter measured the position of the turning point and the stopping point relative to two known positions.

Table 4.1: Experimental conditions for the first of four experiments

Exp	*Target Visibility*	*Environment Type*	*HMD*
Experiment 1		Outdoor 	

Apparatus: Participants wore no special apparatus, and the task was conducted entirely in the real world. Data was collected using the SONIN 10300S ultrasonic depth measurement device and recorded by hand.

Independent Variables: This experiment contained two independent variables: *target location* and *walking direction*. Target location varied between 6, 9, and 12 meters, while walking direction varied between left and right.

Dependent Variables: For each trial, the experimenter gathered two points of data: the *turning point* and the *stopping point* (Figure 1.3). The turning point was the measured location where participants initially stopped, facing where they believed the target to be. The stopping point was the final measured point, at the terminus of the participants' walk.

Using a trilateration approach (Figure 4.2) originating from the field of surveying, the location of these two points was determined, and secondary metrics such as estimated distance and angle, among others, were calculated. Specifically, this approach involved designating and measuring the

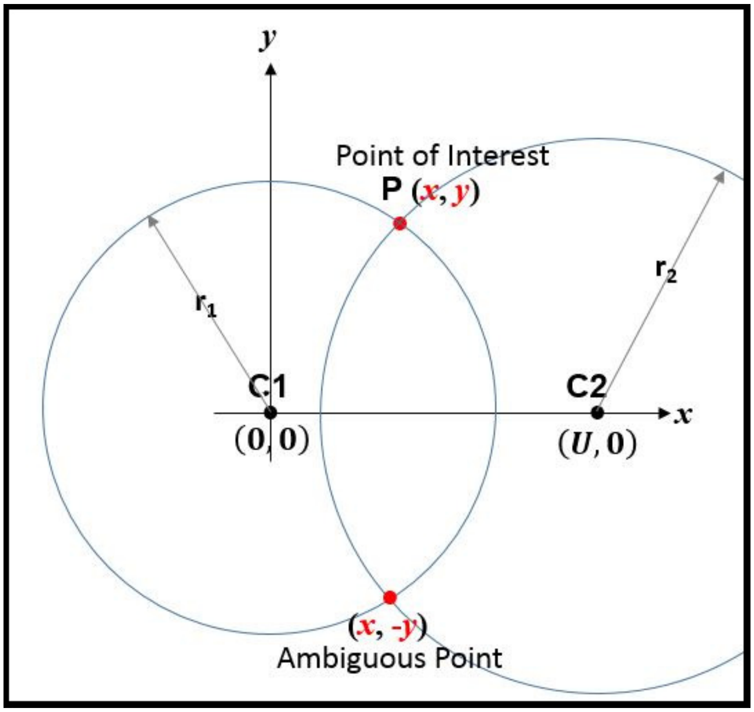


Figure 4.2: Trilateration measurements, using the law of cosines, in a triangle designated with points C1, C2, and P, where P is any arbitrary point not on $\overline{C1C2}$ [69].

distance between two arbitrary fixed points which together formed an axis of a baseline coordinate system. By measuring the distance between each baseline point and the other relevant points (such as the origin and the turning/stopping points for participants), it was possible to calculate those points' exact coordinate positions with the law of cosines (see equations below). In these equations, two points (C_1 and C_2) are used to form a coordinate system (with $\overline{C_1C_2}$ as the x-axis and C_1 as the origin) with respect to any arbitrary point (P); this procedure is used to systematically define the location of the stop and turn points within the experiment.

$$\angle_{PC_1C_2} = \cos^{-1}\left(\frac{(2 * \overline{C_1C_2} + 2 * \overline{PC_1} - 2 * \overline{C_2P})}{(2 * \overline{C_1C_2} * \overline{PC_1})}\right)$$

With $\overline{C_1C_2}$ defining the x-axis and C1 representing (0, 0):

$$y_P = \sqrt{\overline{C_1C_2}^2 + \overline{PC_1}^2 - 2 * \overline{PC_1} * \overline{C_1C_2} \cos(\angle_{PC_1C_2})}$$

$$x_P = \sqrt{\overline{PC_1}^2 - y_P^2}$$

Trilateration-based approaches are particularly useful in an outdoor environment, where establishing a stable coordinate system is key to gathering data. Note that, further, knowledge about participants' location allowed the triangulation task to be constrained; there theoretically exists two triangles that would match a specific measurement, but only one fits the quadrant the participant was known to be in.

In order to create an environment where trilateration could be used, the experimental area was carefully set up through a series of measurements relating each point to the two specified baselines (Figure 4.3). Each point in this sytem was measured and double-checked with a tape measure, and the baseline coordinates were also aligned with two laser levels set at $90°$. In order to insure the accuracy of the in-experiment SONIN measurements, a linear regression was calculated based on the known distances to three points at six, nine, and twelve meters. When applied to measurements taken by the SONIN, this regression corrected for inaccuracies introduced by the changing temperatures, humidities, and other environmental factors. This approach was used to produce the final results for the dependent variables.

Design: Within Experiment 1, target locations were presented serially, with participants first walking in one direction and then the other. The initial direction of the walk was determined

Figure 4.3: Experimenters practicing experimental setup. Tape measures and laser levels were used to set up and validate the experimental area, while the SONIN 10300S ultrasonic depth measurement device was used to measure distances within Experiment 1.

randomly. Distances were presented in a randomized order, with the one constraint being that no distance was repeated twice in a row.

Procedure: Before the experiment, experimenters measured three pre-determined points with the SONIN in order to calibrate readings to environmental conditions. When participants arrived, they signed a consent form and were instructed to fill out a COVID-19 risk form and a general questionnaire (Appendix A). During this process, the experimenter detailed the task and explained certain components of the COVID-19 form and the questionnaire. Participants then completed a practice trial to accustom themselves to the task and insure task comprehension; if that went well, the actual recorded trials began.

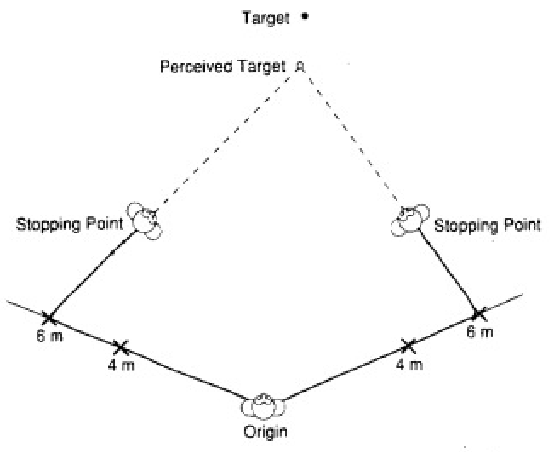
At this juncture, the participant completed the task, as described in the Task section above.

After the experiment, participants were debriefed, and asked about their impressions and any strategies they may have followed (Appendix B). Psychology Research Pool (PRP) participants received course credit for participating, and paid participants received a cash reward of $12.00.

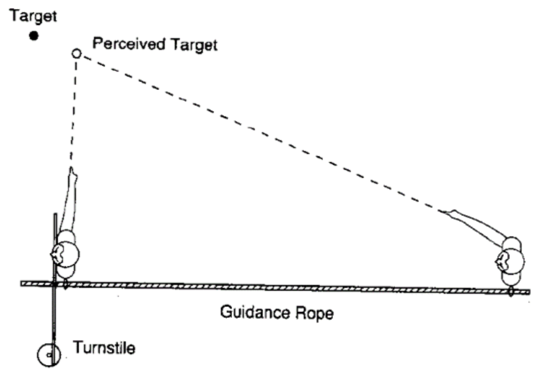
Participants: A total of 13 participants participated in Experiment 1, chosen from among volunteers recruited at Mississippi State University. This number was selected in order to exceed Fukusima et al.'s sample size of 10 participants [33]. Some participants were recruited through the PRP program and some were paid participants. These participants ranged in age from 18 to 28 years old, with an average age of 20. 7 of 13 participants identified as male, and 6 of 13 identified as female.

4.1 Summary

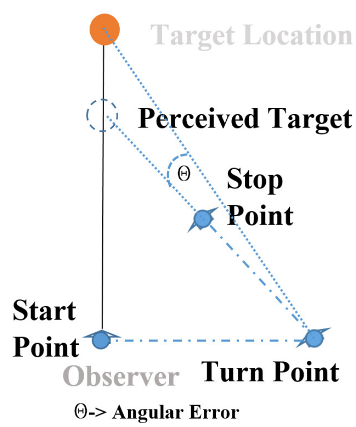
Experiment 1 was designed in order to answer RQ1, **"With what certainty can the triangulation by walking method presented by Fukusima et al. [33] be conceptually replicated?"** This experiment was intended to operate as a trial and test of the modified methodology detailed here in order to ensure an accurate conceptual replication and provide a foundation for further experimentation. In order to accomplish this, Experiment 1 evaluated participants' judgments of perceived location through triangulation by walking in an outdoor environment at distances of six, nine, and twelve meters. The results from this Experiment are presented in Chapter 8 and discussed further in Chapter 9.



(a) The *left/right intersection* method (Copyright ©1997 by American Psychological Association. Reproduced with permission.) [33].



(b) The *origin intersection* method (Copyright ©1997 by American Psychological Association. Reproduced with permission.) [33].



(c) The *angular error* method.

Figure 4.4: Three approaches to error calculation in triangulation by walking

CHAPTER V

EXPERIMENT 2: TRIANGULATION BY WALKING IN AN INDOORS ENVIRONMENT WITHOUT HMD AT ACTION SPACE DISTANCES

Experiment 2 (Table 1.1) was designed to answer Research Question 2.1 (RQ2.1), **"With what certainty can the triangulation by walking method, as presented by Fukusima et al. [33], be conceptually replicated in an indoor environment?"** Environment type has sometimes been associated with anomalous depth perceptions, and various changes to the experimental methodology could have had an effect on depth perception [56, 63, 89, 86, 2, 97]. Further, distances tested in Experiment 2 were nearer than those tested in Experiment 1, and the participant's oblique walking distance was both reduced and notably more constrained than in Experiment 1. In order to answer this question, a modified version of the triangulation by walking method presented in Fukusima et al. was used to evaluate depth perception to real-world targets in an indoor environment.

Experiment 2 was also designed to answer Research Question 2.2 (RQ2.2), **"To what extent do noise cues influence participants' judgment of perceived object location?"** Due to the constraints and limitations of the indoor environment, noise cues from the experimenter's instructions were expected to be nearer and more salient, and, thus, more effective at biasing a participant's depth judgments, than they were in the previously tested outdoor environment. As such, two between-subjects conditions were tested within this experiment: a secure procedure in which experiment instructions were delivered via headphones and a standard procedure in which experiment instructions were delivered in-person with no effort to remove cuing effects.

Hypothesis 2.1 (H2.1, which corresponds to RQ 2.1) was that the results from this experiment would agree with the results from Fukusima et al. [33] and show veridical depth perception through triangulation by walking tasks in an indoor environment, as assessed by a visual comparison. Good certainty was expected in the conceptual replication results, which were visually compared to the results of Fukusima et al., as their numeric results are not available. Hypothesis 2.2 (H2.2, which corresponds to RQ2.2) was that noise cues would not have a significant impact on perceived object location, as evaluated by equal variance T-tests comparing the means of the two distributions. Fukusima et al. [33] found no effect of noise cues on their experimental results, though it should be mentioned that their environment is not likely to have been similar to the indoor environment studied here.

These expectations were based on research that shows, in full-cue situations, judgments to real-world objects to be generally veridical [8, 43, 67, 76, 96]. However, this was also contrasted with research showing that more constrained environments or environmental changes and structure can modify depth judgments [56, 63, 89, 86, 2, 97]. These research findings, in conjunction with each other, create some uncertainty, but it was originally expected that Experiment 2 would provide a further conceptual replication of Fukusima et al.'s results [33].

Task: The purpose of the primary task was to estimate perceived 3D location in an open, indoor environment at action space distances (Table 5.1). The triangulation by walking task was repeated, with a few key changes. Participants observed a target (a 6.7 inch tall soft drink can covered

(a) View from the left starting point. (b) View from the right starting point.

Figure 5.1: The indoor environment of Experiment 2

with pale green construction paper) located 4.18, 5.85, or 7.59 meters away across a large (5.795 m by 7.93 m) indoor room at Mississippi State University (Figure 5.1). These measurements were chosen in order to correspond with tile placements within the room, so that available target locations could be identified in ways that were not discernable to participants (Figure 5.2). These distances corresponded to 12, 18, and 24 tile units (.305 meters) within the room. These distances were interspersed with *confusion distances* in order to disrupt participant memorization of the tested distances (See the Design section). In the standard condition, participant instructions were given by an experimenter present in the room, and participants were instructed to walk toward that experimenter initially (Figure 5.3a). In the headphones condition, participants followed the same procedure, but the experimental instructions were delivered through headphone audio, and the participants walked to a wooden doorstop placed on the floor rather than to an experimenter (Figure 5.3b). Participants were still led back to the starting position by the experimenter in the room; however, since that information was unrelated to target judgment, it is expected that this had no effect. Due to space constraints, the starting point was in a different location for the left and right walking directions, to allow a large enough walking distance for each condition. Beyond these distinctions, the procedure was the same as in Experiment 1.

Table 5.1: Experimental conditions for the first two experiments

Exp	*Target Visibility*	*Environment Type*	*HMD*
Experiment 1		Outdoor 	
Experiment 2		Indoor 	

Figure 5.2: Bean bag placement. Note the low-visibility tape marks with coordinate positions.

Apparatus: Participants wore no special apparatus, and the task was conducted entirely in the real world. The experimental area consisted of a 5.795 meter by 7.93 meter room with a regular, measurable tile floor (Figures 5.1). This floor was labelled with a regularly positioned pale yellow tape, so that floor positions could be easily evaluated and so that participants would have difficulty distinguishing any unique markings on the floor (Figure 5.2). The edge of each tile was labelled and the written text was intentionally not very salient so that, even if participants did notice the tape, no additional depth information would be gained from it. Data was collected using this room's tile-based grid system and recorded by hand.

(a) Verbal instructions. (b) Instructions delievered remotely.

Figure 5.3: The two conditions of Experiment 2. The experimenter gives instructions from outside of the room in condition 2 in order to remove the potential confound of their auditory cues.

Independent Variables: This experiment contained three independent variables: *target location*, *walking direction*, and *audio condition*. Target location varied between 4.18 (12 tile units), 5.85 (18 tile units), and 7.59 meters (24 tile units), while walking direction varied between left and right. Confusion distances were also interspersed among the standard target location.

Dependent Variables: Using the tile-based grid system, the stop and turn points were determined, and secondary metrics such as estimated distance, estimated angle, and left/right bias, among others, were calculated.

Design: Within each experimental session, walking directions were presented serially, with all distances presented in one direction and then all distances going in the other direction tested. The initial direction of the walk was determined randomly. Distances were presented in a randomized order, with the one constraint being that no distance was repeated twice in a row. Note that distance order was not strictly repeated for the second direction tested.

In this experiment, four confusion distances were used, with two presented during left-side walking trials and two presented during right-side trials. These distances were based on a strategy from Ellis et al. [30] used to disrupt participant memorization of target location and were presented at a random time in the distance ordering. The particular confusion distance was randomized, with five potential confusion distances between 4.18 and 5.85 meters and another five possible confusion distances between 5.85 and 7.59 meters.

Procedure: Before the experiment, participants signed a consent form. During this process, the participant was introduced to the task and the questionnaire (Appendix A). After this step, in the headphones condition, the headphone apparatus was set up and a voice call initiated. In the normal condition, no special actions were taken. Participants then performed a practice trial to accustom themselves to the task and insure task comprehension; if that went well, the actual recorded trials began.

At this juncture, the participant completed the task, as described above.

After the experiment, participants were debriefed, and asked about their impressions and any strategies they may have followed (Appendix B). PRP participants received course credit for participating, and paid participants received a cash reward of $12.00.

Participants: A total of 12 participants participated in Experiment 2, chosen from among volunteers recruited at Mississippi State University. This number was selected in order to exceed Fukusima et al.'s sample size of 10 participants [33]. These participants ranged in age from 17 to 32 years old, with an average age of 23. 5 of 12 participants identified as male, and 7 of 12 identified as female.

5.1 Summary

Experiment 2 was designed in order to answer RQ2.1, **"With what certainty can the triangulation by walking method, as presented by Fukusima et al. [33], be conceptually replicated in an indoor environment?"** and RQ2.2, **"To what extent do noise cues influence participant's depth perception judgments?"** This experiment was intended to establish a baseline level of accuracy in an indoor environment for the modified triangulation by walking procedures originally tested in Experiment 1. In order to accomplish this, Experiment 2 evaluated participants' judgments of perceived location through triangulation by walking in an indoor environment at distances of 4.18, 5.85, and 7.59 meters. The results from this Experiment are presented in Chapter 8 and discussed further in Chapter 9.

CHAPTER VI

EXPERIMENT 3: TRIANGULATION BY WALKING TO REAL AND VIRTUAL TARGETS SEEN THROUGH A WINDOW IN AN INDOORS ENVIRONMENT WITH HMD AT ACTION SPACE DISTANCES

Experiment 3 (Table 1.1) was designed to answer Research Question 3 (RQ3), **"What is the effect of object virtuality on perceived object location when the target is viewed through a window?"** Object virtuality in AR has sometimes been associated with anomalous depth perceptions [63, 61, 85], and that could well have held true in this context. In order to answer this question, a modified version of the triangulation by walking method presented in Fukusima et al. [33] was used to evaluate depth perception to real-world and virtual targets beyond a window in an indoor environment (Figures 6.1 and 6.2).

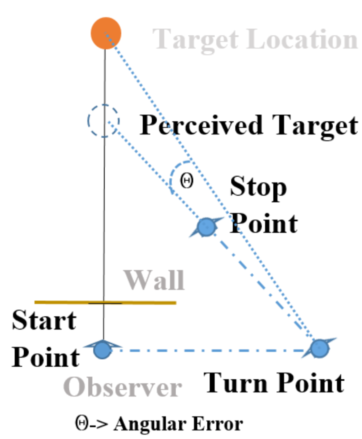


Figure 6.1: The task in Experiment 3, in terms of angular error

Hypothesis 3 (H3) was that object virtuality would have a significant negative effect on perceived object location. This was evaluated by comparing the results from the two experimental conditions: *real-world* targets and *virtual* targets. It was expected that the virtual target condition would be significantly less accurate than the real-world target condition, as evaluated by ANOVA testing.

Object virtuality in AR has sometimes been associated with depth misestimations [63, 61, 85], but has also sometimes been associated with veridical depth estimations [89]. The full impact of this variable is not entirely clear and is likely highly correlated with environmental variables, the specific AR system used, and quality/availability of cues. It was expected that object virtuality would have a negative impact on perceived object location.

Figure 6.2: The wall/window through which participants view target stimuli.

In addition, the effect of viewing an object through a window is likely fairly complex. On the one hand, the presence of a wall likely presents to participants as a source of extra work–which could very easily cause participants to judge distance as farther away, particularly for a walking task [59, 80, 97, 96]. Other factors that could effect judgments to targets include wearing an HMD or headset. In the past, HMDs have been associated with perturbed depth estimations, though that effect may be minimized for more modern HMDs [51, 96, 80, 46, 21]. Viewing targets through a window could also bias depth judgments if the wall is seen as a boundary or environmental anomaly. In previous research, even distinctions as simple as differing types of ground textures have been found to bias depth estimates, so it seems reasonable to conclude that a wall certainly would have that potential [56, 86, 98, 89]. In order to remove the HMD and the window as potential confounds, they are present in both experimental conditions.

Figure 6.3: A participant looking out at the target from the window.

Task: The purpose of the primary task was to estimate perceived 3D location of real and virtual targets seen through a window in an indoor environment at action space distances (Figure 6.3). This task incorporated two new components: the movable wall and the Magic Leap One AR HMD. In order to appropriately prepare, the experimenters set up the wall and disinfected the Magic Leap One before the experiment began (Figure 6.4a). The leg of the wall closest to participants was removed for each trial, and the wall was positioned using pre-set tape marks laid on the floor in order to keep the position consistent between participants and conditions (Figure 6.4b). The position of the wall was selected such that is was .75 meters in front of the participant starting location and such that the window was centered in the participant's view. The window height was calibrated such that participants could easily see all three target positions and that there was visible space between the edges of the target and the window frame. Once the experimental paperwork was filled out, participants were instructed as to how to put on and adjust the Magic Leap One. When participants were comfortable with the headset and Lightpack, they were led through instructions on how to calibrate the Magic Leap One for their vision. Once that process was complete, the experimental program was started up and participants were instructed to calibrate their location to a fiducial fixed to the experimental room's floor (Figure 6.4c). After participants had done this, they were shown a wireframe virtual outline of the room overlapping with the real space. They were instructed to compare this outline to the room and see if there was any visible mismatch between the two. If there was no significant difference between the real and virtual environment, participants were instructed to begin their initial trial and then the experiment; if there was a perceptual difference of more than a few inches, participants were instructed to repeat the fiducial calibration process again. During the virtual target conditions, the Magic Leap One would display the virtual target at the appropriate location and, during real target conditions, the Magic Leap One would display no visual information (Table 6.1, Experiment 3.1 and 3.2). All trials were presented in one direction before trials in the other began. When the walked direction switched in the middle of the experiment, the participant was instructed to face into the corner while the wall was moved from one side to the other. Beyond this, the experimental task remained identical to Experiment 2's headphones condition, with experimenters delivering instructions from another room (Figure 6.5).

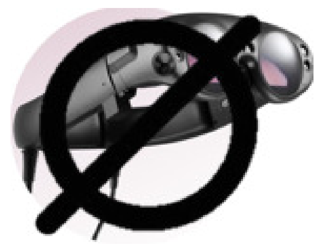
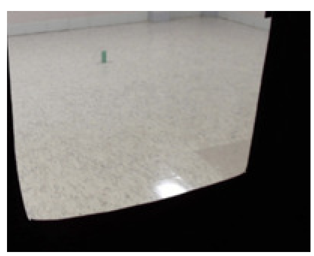
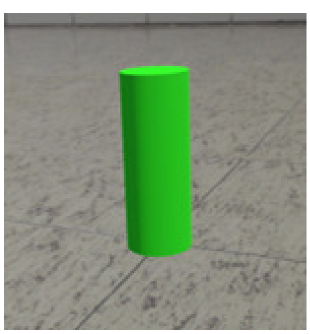
(a) Disinfecting the Leap.

(b) Positioning the wall.

(c) Calibrating the Leap.

Figure 6.4: Pre-trial preparations for Experiment 3.

Table 6.1: Experimental conditions for the first three experiments

Exp	*Target Visibility*	*Environment Type*	*HMD*
Experiment 1		Outdoor 	
Experiment 2		Indoor 	
Experiment 3.1		Real window 	
Experiment 3.2		Real window 	

Apparatus: Participants wore the Magic Leap One AR headset during the experiment. During the virtual condition, the Leap would display stimuli that was designed to be identical, in as many respects as possible, to that of its real-world counterpart. The virtual target was designed to be the same size, shape, and height as the real-world target and was calibrated to appear at the same positions. The brightness of the two targets differed, but the color is intended to be broadly similar, if not identical.

In order to fully implement the x-ray vision task, a custom wall (Figure 6.2) was used in these experiments. This structure is a 7 foot high by 6 foot long wall, with a 24 inch tall by 16 inch wide window directly above its center line. This wall can be easily moved and adjusted, and its position was calibrated so that participants could see all the virtual targets through the wall with both eyes.

Independent Variables: This experiment contained three independent variables: *target location*, *walking direction*, and *object virtuality*. Target location varied between 4.18 (12 tile units), 5.85 (18 tile units), and 7.59 (24 tile units) meters, walking direction varied between left and right, and object virtuality varied between real-world and virtual. Confusion distances were also interspersed among the regular target locations.

Dependent Variables: Using the tile-based grid system, the stop and turn points were determined (Figure 5.2), and secondary metrics such as estimated distance, estimated angle, and left/right bias, among others, were calculated.

Design: Within each experimental session, walking directions were presented serially, with all trials from one walked direction presented before all the trials in the other walked direction were

(a) Walking toward the turn point.

(b) Walking toward the target.

Figure 6.5: A participant performing an Experiment 3 trial.

presented. Distances were presented in a randomized order, with the one constraint being that no distance was repeated twice in a row. Note that distance order was not strictly repeated for the second direction tested. In this experiment, eight confusion distances were used, with two presented per each combination of condition and direction (2 confusion distances * 2 conditions * 2 directions = 8 confusion distances).

For this experiment, condition and initial walking direction were counterbalanced in a four-by-four Latin Square [10]. This formulation allows experimental factors that differ between experiments to be balanced, such that each factor can be tested at each position within the experiment. It is useful here as initial walking direction and initial condition are both potentially important inputs into participant depth perception across the experiment, and the Latin Square technique allows those factors to be balanced, such that each permutation of these variables has equal weight within the experiment [99].

Procedure: In the lead-up to the experiment, the experimenter created a data file and participant record for the participant, using their subject number as a seed for the Latin Square and generating their experimental data sheet. This was used both as input into the experimental code and as a printed data sheet during data collection. Past this, the experiment was conducted as described previously.

Participants: A total of 15 participants participated in Experiment 3, chosen from among volunteers recruited at Mississippi State University. These participants ranged in age from 18 to 63 years old, with an average age of 24. 10 of 15 participants identified as male, and 5 of 15 identified as female. A total of 10 participants was expected to be necessary to reach a statistical power of .8 and an α of .05, based on a power analysis (Figure 6.6). To calculate this, f was first found, using an effect size of .6. Using Cohen's formula $f = .5 * d$ for two groups [17], $f = .3$ in the GPower plot. As such, a minimum of 10 participants was required, but 15 actually participated in the experiment in order to exceed the minimum and account for any misestimated variables within the power analysis.

6.1 Summary

Experiment 3 was designed in order to answer RQ3, **"What is the effect of object virtuality on perceived object location when the target is viewed through a window?"** This experiment was intended to evaluate the effects of object virtuality on participant performance, particularly when compared to a baseline performance while wearing an HMD and judging target position through a window in a wall. In order to do this, Experiment 3 evaluated virtual and real target

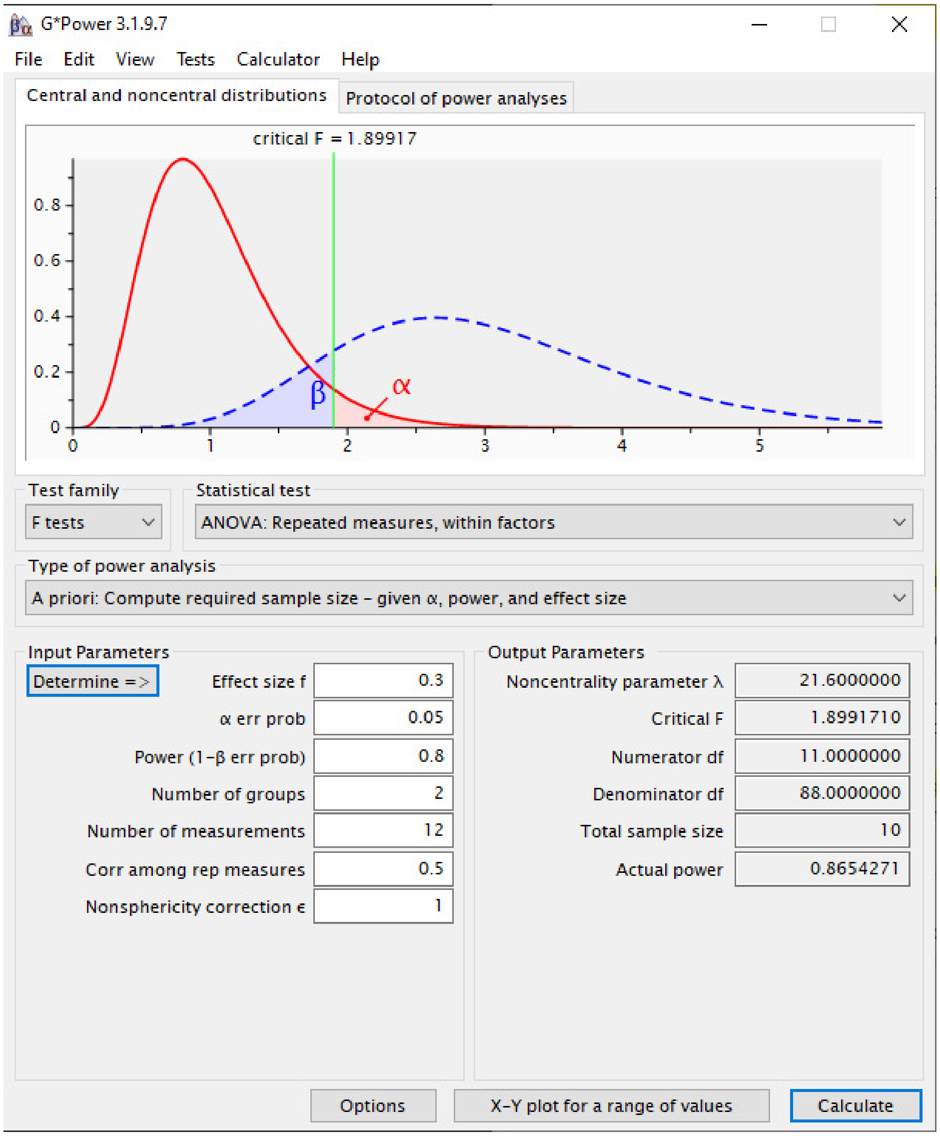


Figure 6.6: The initial power analysis for Experiment 3.

conditions at distances of 4.18, 5.85, and 7.59 meters in an indoors triangulation by walking task, with participants using an HMD and making judgments through a physical window in a wall.

CHAPTER VII

EXPERIMENT 4: TRIANGULATION BY WALKING TO VIRTUAL TARGETS SEEN THROUGH DIFFERING VIEWING CONDITIONS IN AN INDOORS ENVIRONMENT AT ACTION SPACE DISTANCES

Experiment 4 (Table 1.1) was designed to answer Research Question 4.1 (RQ4.1), **“What is the effect of a fully opaque wall on perceived object location?”** Experiment 4 was also designed to answer Research Question 4.2 (RQ4.2), **“What is the effect of a virtual window and frame against an opaque wall on perceived object location?”** These questions are novel to this research, but conflicts between occlusion and other depth cues, along with perceptual issues related to windows and virtuality implied that viewing condition would have a significant impact on perceived object location. In order to answer these questions, a modified version of the triangulation by walking method presented in Fukusima et al. [33] was used to evaluate depth perception to virtual targets presented beyond a real window, an opaque wall, or a virtual window in an indoor environment.

Hypothesis 4.1 (H4.1) was that the presence of the fully opaque wall would have a significant negative effect on perceived object location. This was evaluated by comparing results from the opaque wall condition with the other tested conditions (real window and virtual window). It was expected that the opaque wall results would be significantly less accurate than any other tested result within Experiment 4. This hypothesis was tested by multiple ANOVA tests (one with both of the other conditions).

Hypothesis 4.2 (H4.2) was that the virtual window and frame would have a significant negative effect relative to the real window condition. It was expected that the virtual window and frame would work to improve depth perception accuracy to the virtual target as compared to accuracy to a fully occluded virtual target; however, this intervention was still expected to be less accurate than depth estimation through a real-world window. This was evaluated by comparing the results from the virtual window condition with those of both other conditions (real window and opaque wall). This hypothesis was also tested by multiple ANOVA tests (one set of which overlapped with testing for Hypothesis 4.1).

The conflict between occlusion and other depth cues has been observed to significantly impair depth perception judgments [9, 65, 34, 89]. It seemed very likely that this effect could also be observed in this experiment; even though technology may have improved since the cited research, the underlying perceptual context has not changed.

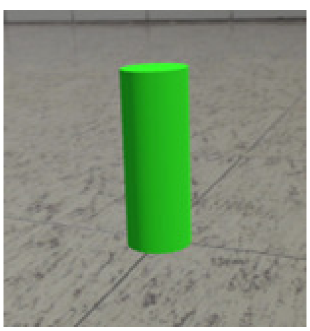
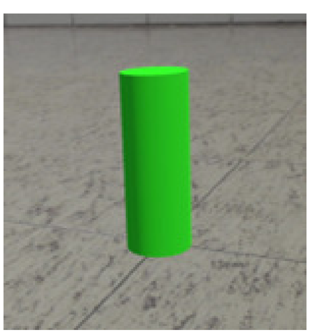
Introducing the window metaphor provides extra visual information that seems likely to help humans contextualize virtual targets as objects seen through a window (Figure 3.4). This metaphorical construct was likely to provide a context in which virtual scene information could be more easily understood, by helping participants parse the competing occlusion and stereopsis/motion parallax cues. Indeed, previous research showed that the window metaphor does a have positive effect on depth perception, though the size of that effect is still uncertain [9, 65, 34]. As a result, the window metaphor was expected to improve depth estimations in comparison to a fully occluded environment with no visualization aids.

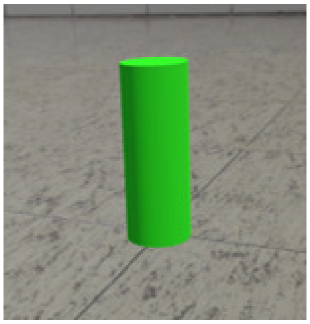
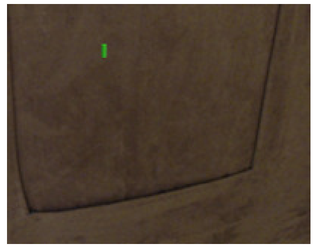
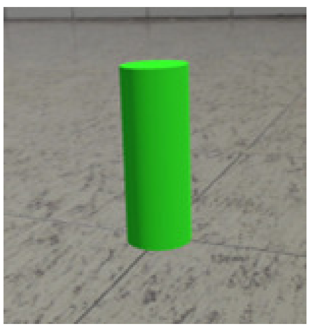
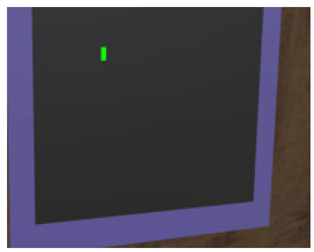
Figure 7.1: A participant performing a trial in the opaque wall condition.

Task: The purpose of the primary task was to estimate perceived 3D location of targets seen through a viewing condition (real window, opaque wall, virtual window) in an indoor environment at action space distances (Table 7.1). A participant performing such a task in the opaque wall condition is visible in Figure 7.1. Other than this, the experimental task remained identical to Experiment 3.

Table 7.1: Experimental conditions for all four experiments

Exp	*Target Visibility*	*Environment Type*	*HMD*
Experiment 1		Outdoor 	

Continuation of Table 7.1			
Exp	*Target Visibility*	*Environment Type*	*HMD*
Experiment 2		Indoor 	
Experiment 3.1		Real window 	
Experiment 3.2		Real window 	
Experiment 4.1		Real Window 	

Continuation of Table 7.1			
Exp	*Target Visibility*	*Environment Type*	*HMD*
Experiment 4.2		Opaque wall 	
Experiment 4.3		Wall w/virtual window 	

Apparatus: The apparatus remained the same in Experiment 4, save for the addition of a panel that could be used to cover the open section of the cloth wall, making it fully opaque. The virtual window, while visually distinct from the real-world window, was designed to be the same size and in the same location as the real-world window (Table 7.1).

Independent Variables: This experiment contained three independent variables: *target location*, *walking direction*, and *viewing condition*. Target location varied between 4.18 (12 tile units), 5.85 (18 tile units), and 7.59 (24 tile units) meters, walking direction varied between left and right, and viewing condition varied between real-world window, opaque wall, and virtual window.

Dependent Variables: Using the tile-based grid system, the stop and turn points were determined, and secondary metrics such as estimated distance, estimated angle, and left/right bias, among others, were calculated.

Design: Within each experimental session, walking directions were presented serially, with all distances in each condition presented in one direction and then all distances in each condition going in the other direction tested. Distances were presented in a randomized order, with the one constraint being that no distance was repeated twice in a row. Note that distance order was not strictly repeated for the second direction tested. In this experiment, twelve confusion distances were used, with two presented during each combination of condition and direction (2 confusion distances * 3 conditions * 2 directions = 12 confusion distances).

For this experiment, condition and initial walking direction were counter-balanced in a six by six Latin Square [10].

Procedure: The experiment was conducted as described previously.

Participants: A total of 20 participants participated in Experiment 4, chosen from among volunteers recruited at Mississippi State University. These participants ranged in age from 18 to 63 years old, with an average age of 25. 14 of 20 participants identified as male, and 6 of 20 identified as female. A total of fourteen participants was expected to be necessary to reach a statistical power of .8 and an α of .05, based on a power analysis (Figure 7.2) for each hypothesis test. To calculate this, f is first found, using an effect size of .6. Using Cohen's formula $f = d/2 * \sqrt{(k+1)/(3*(k-1))}$ for three groups [17], $f = .24$ in the GPower plot. As such, a minimum of 14 participants was

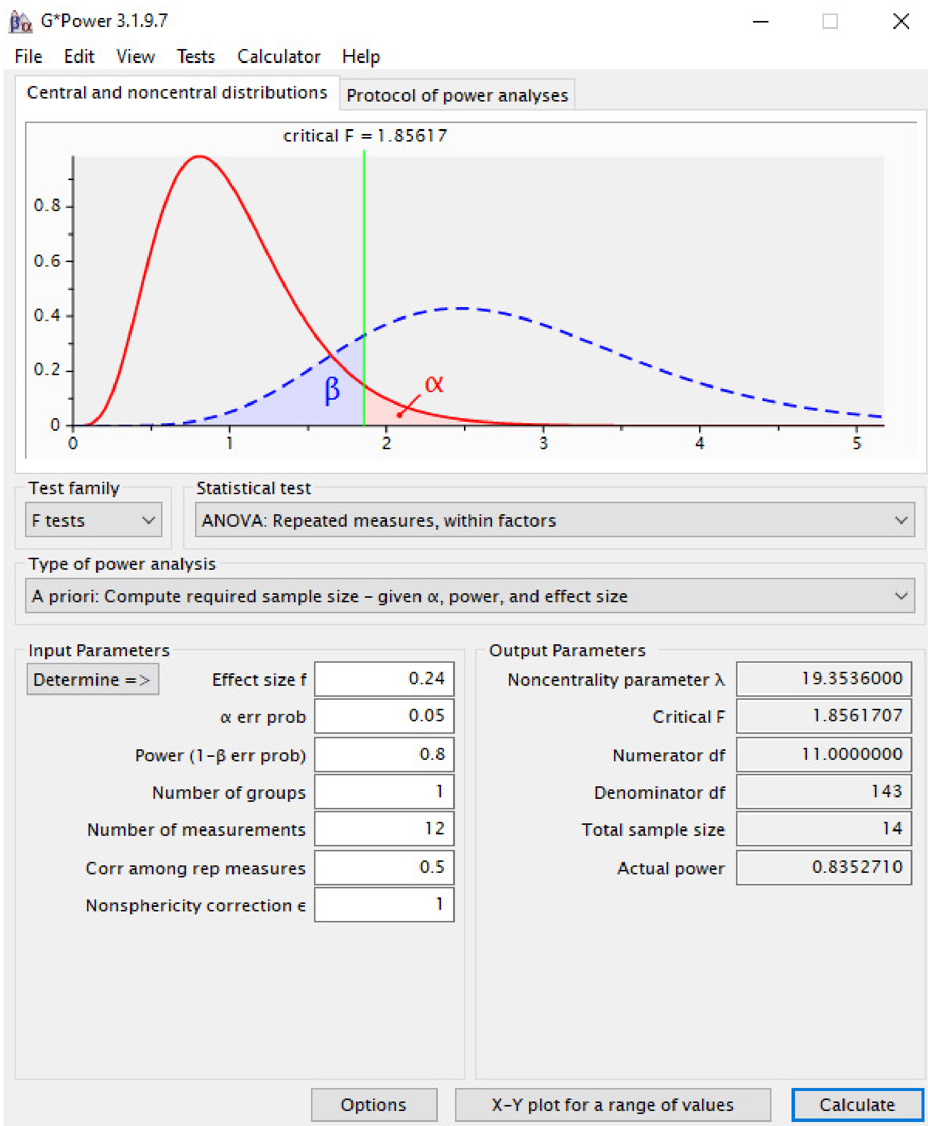


Figure 7.2: The initial power analysis for Experiment 4.

required, but 20 actually participated in the experiment in order to exceed the minimum and account for any misestimated variables within the power analysis.

7.1 Summary

Experiment 4 was designed in order to answer RQ4.1, **"What is the effect of a fully opaque wall on perceived object location"** and RQ4.2, **"What is the effect of a virtual window and frame against an opaque wall on perceived object location?"** This experiment was intended to evaluate the effectiveness of x-ray vision and compare it to its nearest ecologically valid context, vision to an object seen through a real window. In order to answer these questions, a viewing condition variable is introduced with three levels: vision through a real window to a virtual target displayed in an HMD (a condition identical to Experiment 3's virtual target condition); vision through a virtual window to a virtual target, both displayed in an HMD; and vision through an opaque wall to a virtual target displayed in an HMD. As in Experiment 3, participants judged distances to the target through a wall with a window and while wearing an HMD. Experiment 4 tested participants' judgments of perceived location across the three viewing conditions through triangulation by walking in an indoor environment at distances of 4.18, 5.85, and 7.59 meters.

CHAPTER VIII

RESULTS

In order to answer the main research question presented in Chapter 1, **"Can a real window be replaced with an AR window?"**, and all the supporting research questions, it is necessary to analyze the results collected in Experiments 1 through 4, presented in Chapters 4 through 7. The first step in this process is discussing and detailing the overall analysis methods and statistical approaches used in examining the data. Then the results for each experiment will be explored sequentially and outliers examined. Finally, each experimental hypothesis will be statistically evaluated before being fully discussed in Chapter 9.

8.1 Analysis Methods

The first analysis method addressed in this research comes naturally, as it is the method used in Fukusima et al. [33]. This methodology, referred to here as the *left/right intersection* method takes a participant's left and right walks and finds the intersection of their walked paths. This intersection point is considered to be the location where the participant perceives the target, and the amount of error can then be found by calculating the distance between the perceived target location and the actual target location. This approach is visible in Figure 4.4a and, using actual participant data, in Figure 8.1 here.

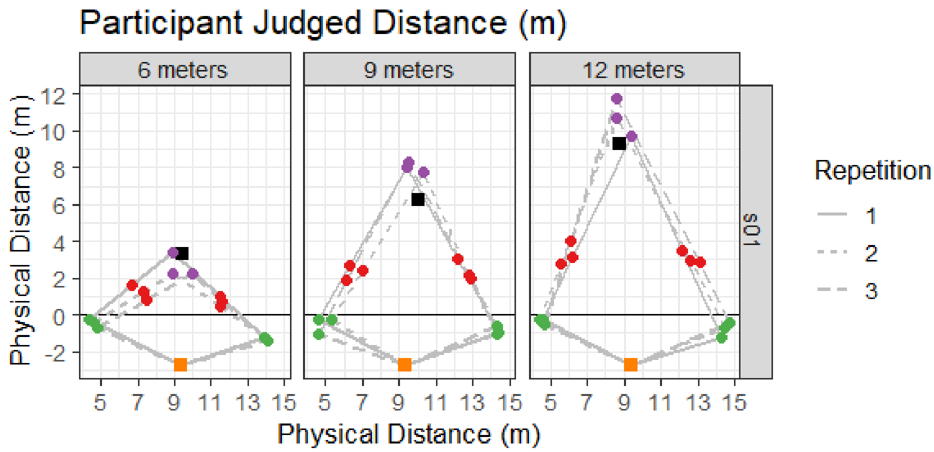


Figure 8.1: An example of the left/right intersection methodology from Experiment 1 ($N = 1$). The orange points represent starting location; green, turn points; red, stop points; purple, judged distance; and black, target location. Target distance from the starting point is labelled at the top of the graph.

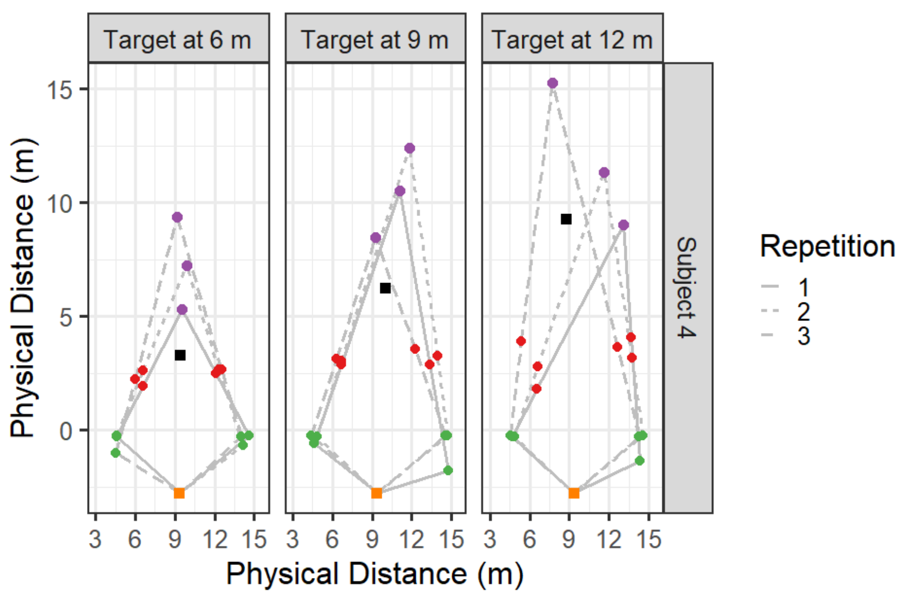


Figure 8.2: Experiment 1 left/right intersection demonstrating methodological issues such as combined over- and under-estimation judgments into one result ($N = 1$). The orange points represent starting location; green, turn points; red, stop points; purple, judged distance; and black, target location. Target distance from the starting point is labelled at the top of the graph.

In Experiment 1, the left/right intersection method produced data that was in line with what was expected (Figure 8.1), but a few key issues quickly became apparent. The first is that left/right intersection halves the available data, reducing the statistical power and significance of the results; participants make two depth judgments to produce only a single result. In addition, this has the effect of reducing the error artificially, with some exceptions as in Figure 8.5. In left/right intersection, an overestimation error in one direction can combine with an underestimation error in the other direction to produce a result that is nearer to the target than it would be otherwise (Figure 8.2); more commonly, a large error in one direction can be counteracted by a more accurate estimation in the other direction, again producing a result with artificially low error (Figure 8.2). Even further, the rationale for the left/right intersection method is weakened in Experiments 2 through 4, where left and right location judgments are displaced from each other by a significant amount of time. This set of errors makes the left/right intersection method less appealing as an analysis approach; observing this, alternative approaches were sought.

With these issues under consideration, the *origin intersection* method was investigated as a potential alternative. In this method, demonstrated conceptually in Figure 4.4b and with actual participant data in Figure 8.3, judged location is calculated independently for the left and right walks. This is accomplished by finding the intersection of the participant's initial viewing vector with the participant's walked path on walks in both directions.

Unfortunately, while the origin intersection method does eliminate the previously discussed types of data problems, both it and left/right intersection still suffer from yet further problems (Figures 8.4 and 8.5). For both methods, small errors in estimation are generally well-described; however, there are a number of problems with large errors and misestimations. For one, a large

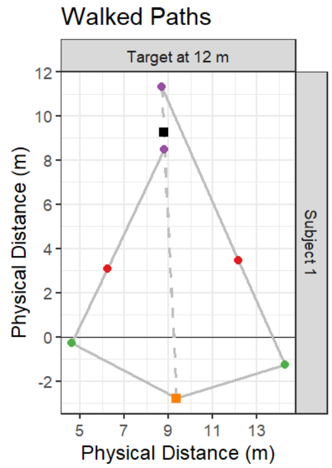
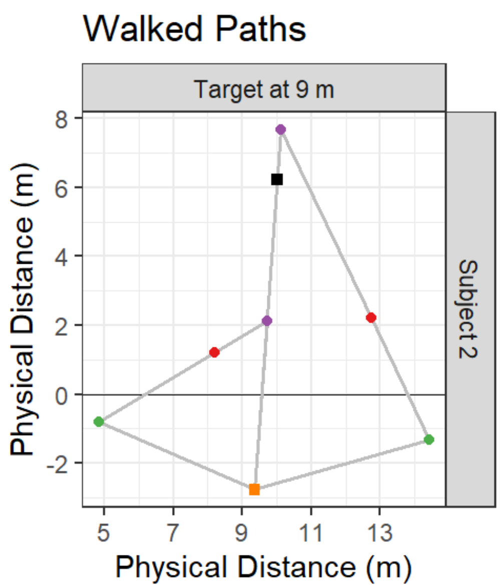


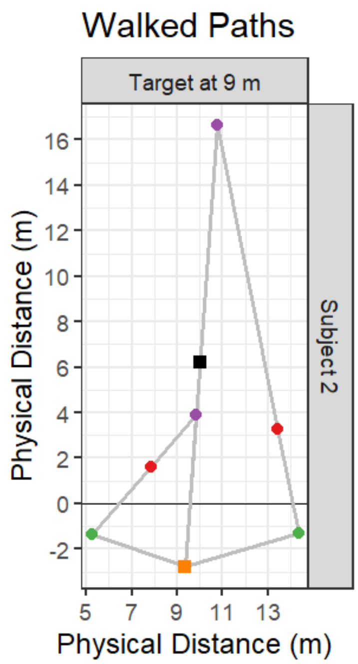
Figure 8.3: An example of the origin intersection method from Experiment 1 ($N = 1$; 2 trials). The orange points represent starting location; green, turn points; red, stop points; purple, judged distance; black, target location. Target distance from the starting point is labelled at the top of the graph.

underestimation error is artificially reduced (Figure 8.4a) as compared to a large overestimation error (Figure 8.4b). It is clear that participants do not believe that the target is over 100 meters away–overestimation errors are simply not well-described by these methods. As an extension, both methods perform poorly in the case where participants' estimations are so inaccurate that they do not even intersect in the forward direction (Figure 8.5)! This outcome is more likely for left/right intersection, but still methodologically possible with origin intersection. In these cases, a participant has turned farther than they intended, and this is methodologically interpreted as a positional depth estimate behind what the participant actually intended. This is clearly not representative of participant perception and so the origin intersection method also seems insufficient for reporting perceived position.

In contrast to the above methods, the *angular error* method does not produce a specific distance estimation at all. Instead, the angular error method, demonstrated conceptually in Figure 4.4c and

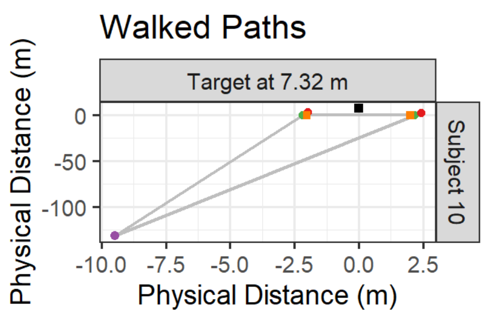


(a) A large underestimation judgment on the left.

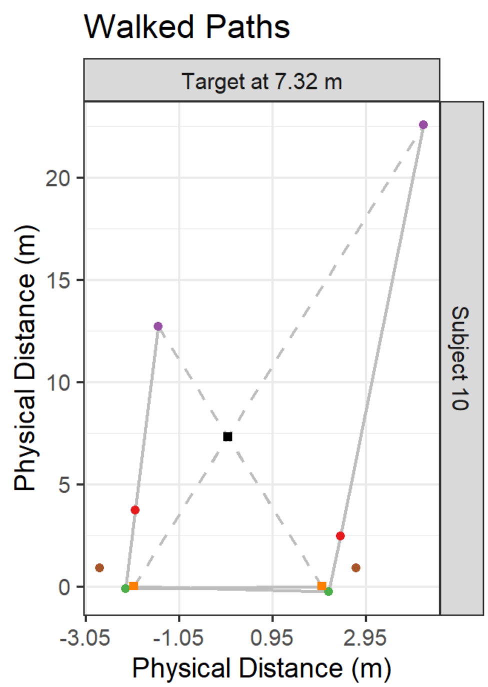


(b) A large overestimation judgment on the right.

Figure 8.4: The origin intersection method ($N = 1$; 2 trials each). The orange points represent starting location; green, turn points; red, stop points; purple, judged distance; black, target location. Target distance from the starting point is labelled at the top of the graph.



(a) Left/Right intersection.



(b) Origin intersection method.

Figure 8.5: A comparison of the left/right intersection and origin intersection methods from Experiment 2 where the walked path does not converge in the positive direction but instead intersects at a large negative value ($N = 1$; 2 trials). The orange points represent starting location; brown, experimenter or wood chip position; green, turn points; red, stop points; purple, judged distance; black, target location. Target distance from the origin is labelled at the top of the graph. The dotted line represents the participant's initial target viewing vector.

with actual data in Figure 8.6, evaluates the angle of the participant's turn as compared to the angle the participant would have had to turn to walk straight toward the target location. This value is calculated through the following formula: $A = cos^{-1}(\frac{b^2+c^2-a^2}{2bc})$, with a representing the distance between the stop point and the target, b representing the distance between the turn point and the stop point, and c representing the distance between the turn point and the target. The result of this formula is the angular error, or the difference between the participant's turn angle and the correct turn angle. This approach avoids the geometric scaling issues of the previous two approaches and produces an angle encompassing the judged error for each participant trial. It was expected that this variable will vary linearly with participant error and represent a more valid metric than the previous two approaches.

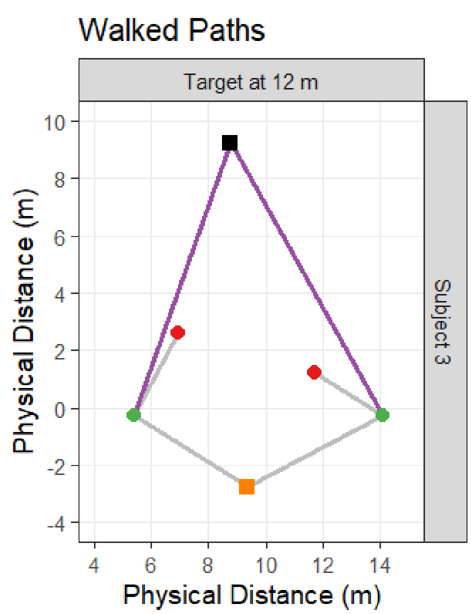


Figure 8.6: An example of the angular error method from Experiment 1 ($N = 1$; two trials), where the error measure is the difference between the participant turn angle and the correct turn angle. The orange points represent starting location; green, turn points; red, stop points; black, target location. Target distance from the starting point is labelled at the top of the graph. The purple line represents the actual path from the turning point to the target.

Overall, then, the angular error method seems to represent the best approach to calculating error and misestimation in these medium-field triangulation by walking tasks. This approach is the predominant methodology used throughout the rest of this work, with results presented using the other methods to highlight certain features of the data or to directly compare to Fukusima et al. [33]. Beyond this, however, the angular error method represents the most comprehensive and complete of these approaches and so will be the predominant one used.

8.2 Statistical Approach

In addition to discussing the analysis methods used to evaluate perceived location in the presented experiments, it is also important to briefly discuss the statistical approach used in the hypothesis testing and data analysis. Analysis of variance (ANOVA) testing is standard practice for experimental outcomes in data science; as such, this is the statistical approach that will be used in testing for significance.

More specifically, the general statistical test used was repeated-measures ANOVA. This accounts for the repeated trials that were in each experiment and allows for more power in the analysis. When more than two conditions were tested, Mauchly's test of sphericity was conducted, and if this test indicated that sphericity was violated, the Greenhouse-Geisser correction is reported and applied. A general linear model was used as well, based on differing assumptions related to repeated measures correlations. This approach is incorporated for several variables for which findings are marginal or not significant, in order to fully evaluate their significance.

Further, in discussing significant statistical results it is important to include both the calculated p value and an effect size measure. The effect size for these experiments and results will most often be η^2. In order to best understand this variable, generally accepted effect sizes are that an η^2 value of .01 is small, .06 is intermediate, and .14 is large, though various conditions may alter these effect sizes as measured [18]; as always, these values are best approached with an understanding of the experimental context. As is best practice and in order to more fully communicate experimental results, both the p value and η^2 will be detailed in any statistically significant results.

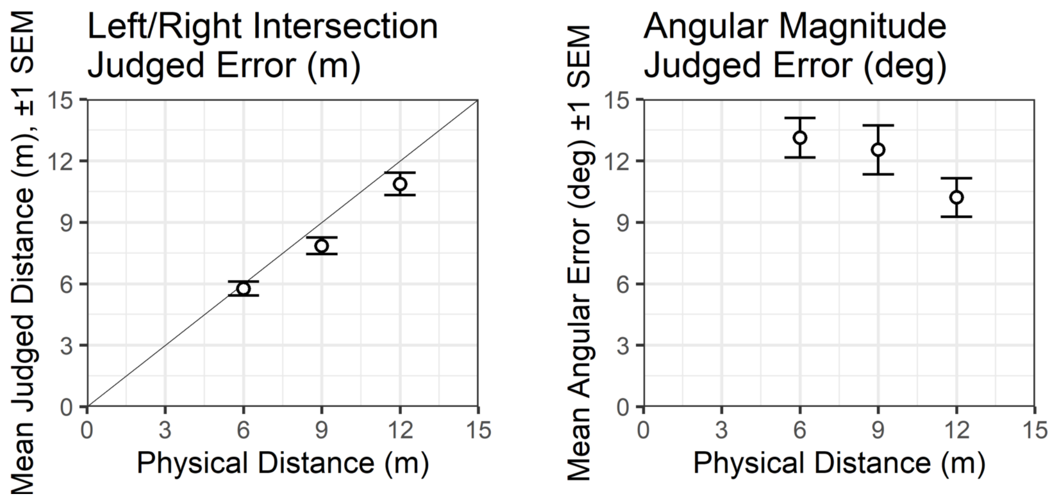
It is also worth mentioning that, for ANOVA-based testing and angular error, the absolute value of the angular error result was used. This allowed ANOVA-based tests to better detect deviations in the size of the error; without using absolute value, positive and negative deviations would tend to cancel each other out in the analysis. This has also been the standard for some prior research investigating depth perception through homing tasks in enclosed environments [7].

8.3 Experimental Results

The results for each experiment within this research will first be presented as a general overview and then in more detail with graphs and statistics highlighting key elements of the data. A presentation of outlier classification and approach will also be covered here, as well. The primary analysis within this section will be angular error, but results from left/right intersection will be presented as well, when comparing to Fukusima et al. [33].

8.3.1 Experiment 1

In Experiment 1, participants walked to targets in a flat, open outdoor environment, with target distances of six, nine, and twelve meters. Results are presented in Figure 8.7a in terms of left/right intersection and in Figure 8.7b in terms of angular error. Note that left/right intersection is important in this experiment, as this allows for a direct comparison to Fukusima et al. [33].



(a) Left/Right Intersection.

(b) Angular Error Magnitude.

Figure 8.7: A comparison of left/right intersection and angular error analysis for Experiment 1 $(N = 13)$. For both graphs, the error bars represent one standard error of the mean (SEM).

H1, the hypothesis for Experiment 1, was that the results would agree visually with the results of Fukusima et al. [33]. These results can be seen in Figure 8.8 and show a successful conceptual replication of Fukusima et al.'s work. These results seem to show that left/right intersection analysis supports veridical depth perception in an outdoor environment–a result very different from the findings of Experiment 2.

There is a main effect of distance for the left/right intersection method ($F_{(2,24)} = 8.8, p < .005$, $\eta^2 = .21$ [large effect size]). As expected, participant depth judgments vary linearly with the target distance; participants tend to walk accurately toward where the target is [8, 43]. There is no significant effect of distance for angular error ($F_{(2,24)} = 1.9, p > .05$). This is also as expected, since the angular error measure would not be expected to vary significantly with distance, particularly within the medium field.

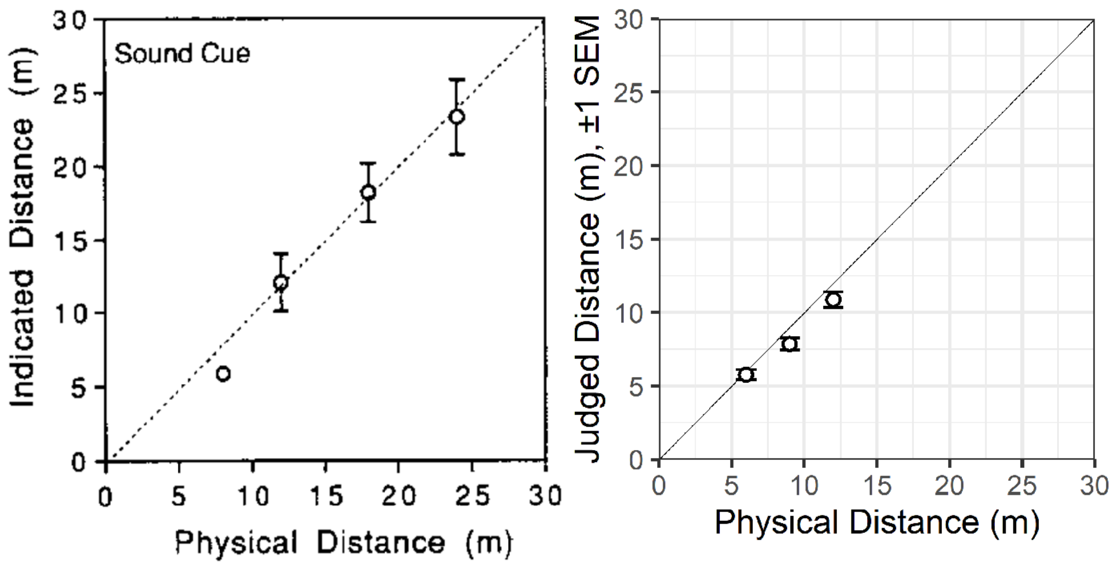
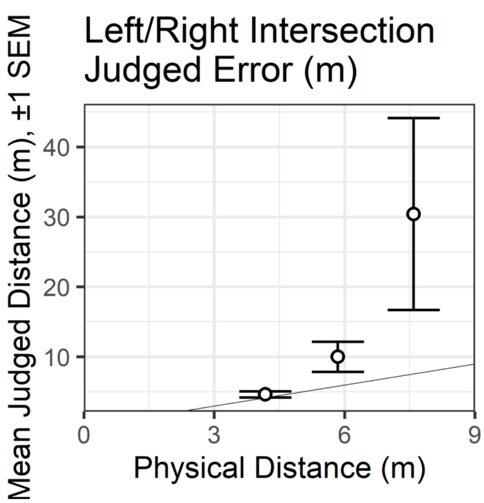


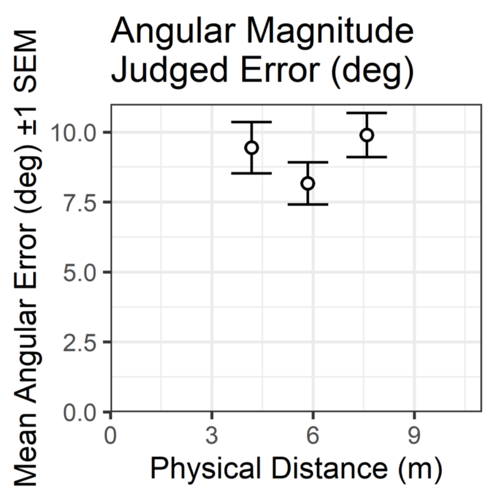
Figure 8.8: Experiment 1 results ($N = 13$, right), as compared to Fukusima et al.'s [33] Experiment 4 ($N = 10$, left). For both graphs, the error bars represent one SEM, and both experiments exhibit normal, unrestricted sound cues.

Outliers In Experiment 1, the left/right intersection approach turned up one significant outlier in subject 4 who had unusually high error for the Experiment (Figure 8.2); however, the unusual nature of this error was substantially reduced when using the angular error method (Figure D.1). As such, it seems that this anomalous distance estimation is a natural consequence of the geometric position methods and that this measurement is not representative of categorically unusual or mismeasured error. There was also another single trial outlier in subject 12 (Table D.1 in Appendix C) that dramatically differed from the rest of that subject's data. This judgment was replaced with the average error from the other two trials the participant performed at that distance. For this experiment, the SONIN calibration function was also applied to participant data, and a final correction was made to fix small positional errors that occurred when measurements were very nearly on the line between baseline points. This correction was needed because the values, as measured, were not geometrically possible; the trilateration circles created by these measurements were too small to intersect and so no point existed physically which could match the measurement results. In order to fix these errors, the measured distances were increased such that they described a real-world position, and an epsilon value of a centimeter was added to prevent quantization errors. As such, all 13 participants are included, with adjustment, in this data.

8.3.2 Experiment 2



(a) Left/Right Intersection.



(b) Angular Error Magnitude.

Figure 8.9: A comparison of left/right intersection and angular error analysis for Experiment 2 $(N = 12)$.

In Experiment 2, participants walked to targets in a flat, enclosed indoor environment, with target distances of 3.66, 5.49, and 7.32 meters. Results are presented in Figure 8.9a in terms of left/right intersection and in Figure 8.9b in terms of angular error. The observed error in the left/right intersection method is dramatically out of scope with expected results; as such, angular error is instead used for proceeding experiments. Results are further presented by condition in Figure 8.10.

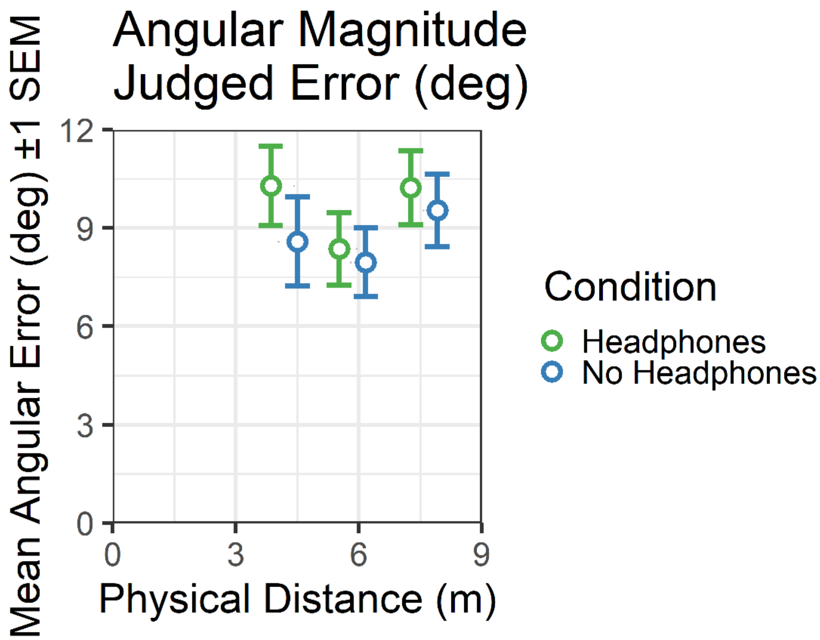


Figure 8.10: Experiment 2 angular error magnitude by condition $(N = 12)$. Left/right displacement of the conditions is for visual clarity and does not represent any difference in distance.

H2.1, the first hypothesis for Experiment 2, was that the results would agree visually with the results of Fukusima et al. [33] and show veridical depth perception through triangulation by walking tasks in an indoor environment. These results can be seen in Figure 8.11 and are notably different from Fukusima et al.'s results. These divergent findings demonstrate the impact of enclosed, indoor environments on depth perception; in doing so, these results show what might be expected for Experiment 3 and 4, as both experiments make use of the same indoor environment in more constrained viewing conditions.

H2.2, the second hypothesis for Experiment 2, was that noise cues would not have a significant effect on perceived object location. Indeed, no significant effect of noise cues on participant depth judgments was found for either the left/right intersection $(F < 1)$ or angular error magnitude

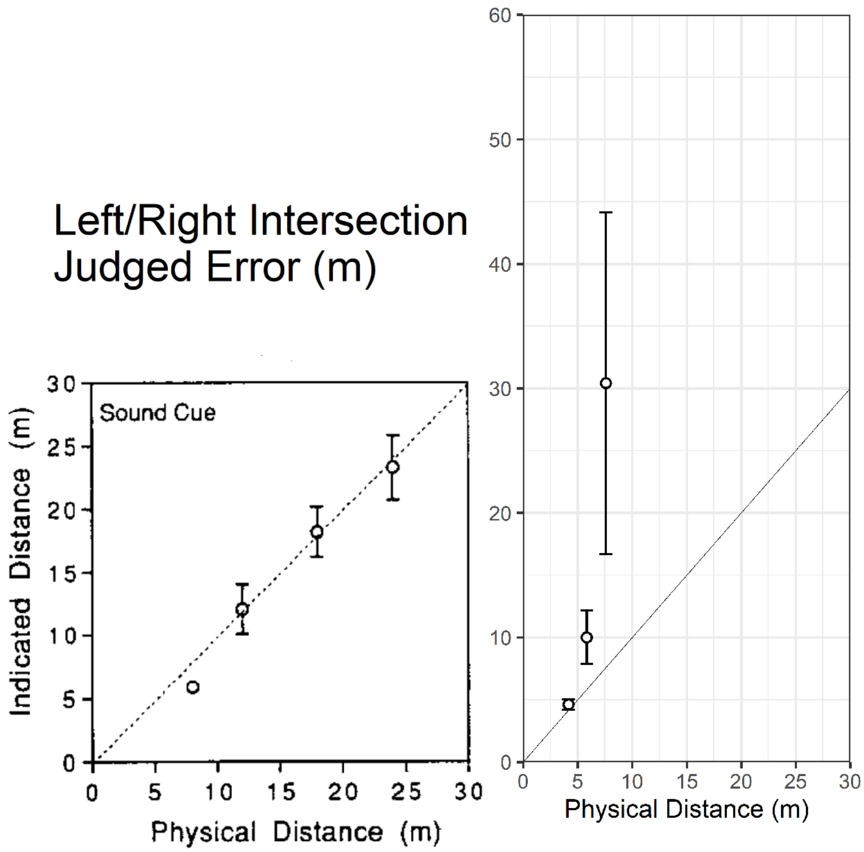


Figure 8.11: Experiment 2 results ($N = 12$, right), as compared to Fukusima et al.'s [33] Experiment 4 ($N = 10$, left). For both graphs, the error bars represent one SEM, and both experiments exhibit normal, unrestricted sound cues. For both graphs, the error bars represent one SEM, and both experiments exhibit normal, unrestricted sound cues.

$(F < 1)$ analysis. This effect can be seen visually in Figure 8.10 and coincides with the findings of Fukusima et al. [33].

In Experiment 2, there is no significant effect of distance in either the left/right intersection method ($F_{(2,24)} = 3.2, p > .05$) or in the angular error method ($F_{(2,24)} = 1.0, p > .05$).

Outliers In Experiment 2, the move away from left/right intersection was completed, largely because it became clear that left/right intersection results were not the best measures of error in these experiments (Figure 8.9a). This evaluation is based on procedural reasons, such as left and right judgments being displaced from each other, as well as analytical reasons, such as geometrically scaling error rates and halved participant data. At this juncture, outliers were determined based on potential procedural error or unusually high angular error. Since these sorts of homing tasks naturally are associated with a high degree of angular error [7, 16], the threshold for outliers was rather steep, at 50°. None of the trials in Experiment 2 suffered from errors greater than the threshold; indeed, the only observed angular error greater than 30° can be seen in Table D.1 in Appendix C and was an underestimation of 33.45°. As such, no outliers were corrected and no trial results were modified for Experiment 2.

8.3.3 Experiment 3

In Experiment 3, participants walked to targets in a flat, enclosed indoor environment, with target distances of 3.66, 5.49, and 7.32 meters. In this experiment, participants wore an HMD and judged the distance to targets presented through a real window. Results are presented in Figure 8.12 in terms of angular error. Results are further presented by condition in Figure 8.13.

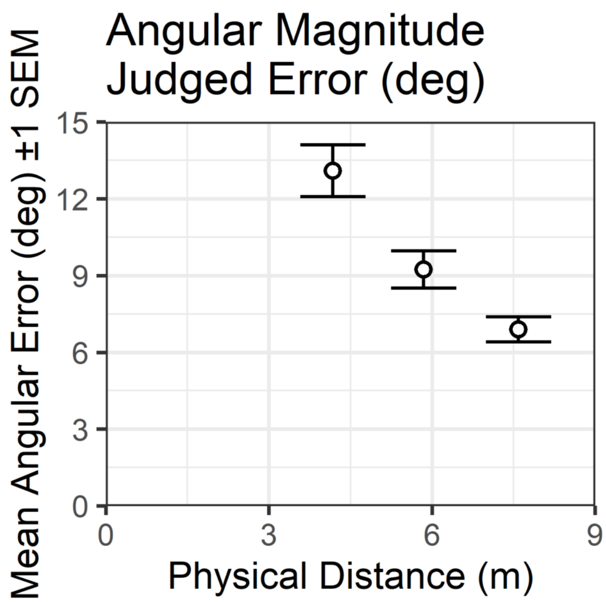


Figure 8.12: Experiment 3 angular error magnitude $(N = 15)$.

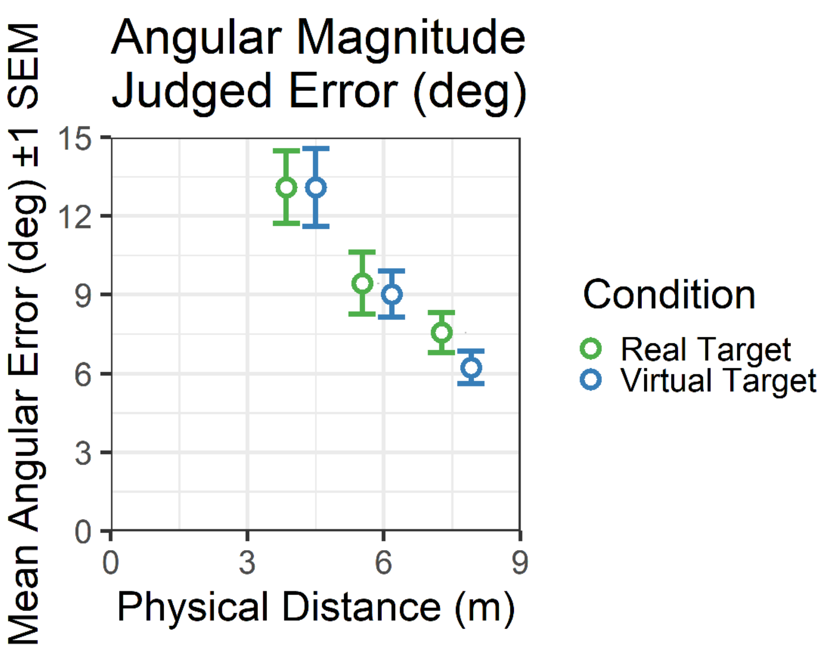


Figure 8.13: Experiment 3 angular error magnitude by condition $(N = 15)$. Left/right displacement of the conditions is for visual clarity and does not represent any difference in distance.

H3, the hypothesis for Experiment 3, was that object virtuality would have a significant negative effect on participant depth perception, as measured by ANOVA tests comparing the real target and virtual target conditions. No statistically significant effect of condition was found ($F < 1$); this can be seen visually in Figure 8.13 and is a surprising result, based on previous research [47, 90, 63, 85, 37, 61, 34].

With the meaningfulness of this result, it is helpful to analyze it in further depth. As such, a general linear model is created and used to evaluate this hypothesis. For H3, no significant effect of object virtuality was found in this linear model ($F < 1$).

A potential confound within this experiment is participant memorization and training effects. It is possible that participants memorized the locations of the three main distances presented (3.66, 5.49, and 7.32 meters) and relied on that memorized distance rather than their own perception. In order to visualize this potential effect, the confusion distances and regular distances are presented together in Figure 8.14. Visually, there does not appear to be an effect of memorization on participant depth judgments.

A second major potential confound is the potential existence of training effects. It is possible that the order in which participants perform each condition could impart additional information or understanding to the participant, which in turn could impact depth judgments. This confound is countered by the experimental design. Using Latin Squares [10] ensures that order effects are balanced out within the experiment, though it possible that certain orderings still impart extra information or biases to the participant. Participants could also be unconsciously biased by the information presented in ways that they themselves could be unaware of. In order to visualize this potential effect, both conditions are displayed in Figure 8.15, with participants split into a group where that condition was presented first and one where that condition was presented last. From this data, there does not appear to be any observable training effects.

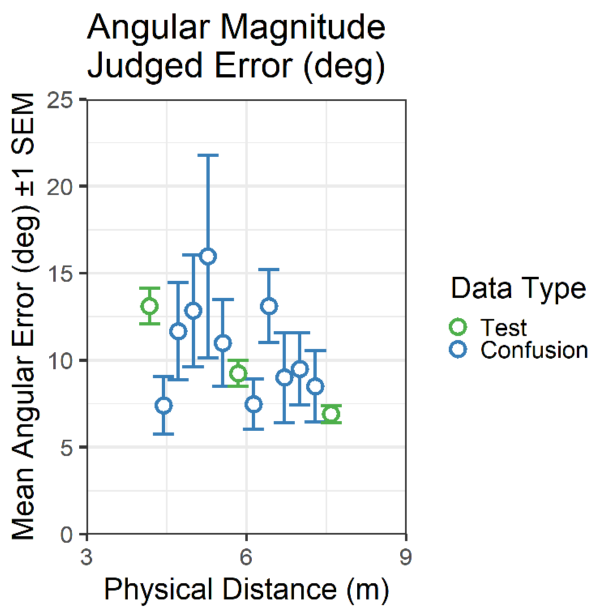
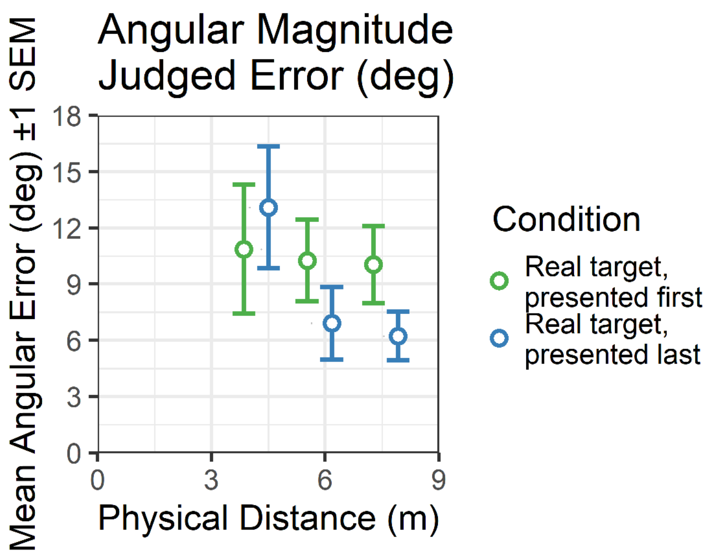
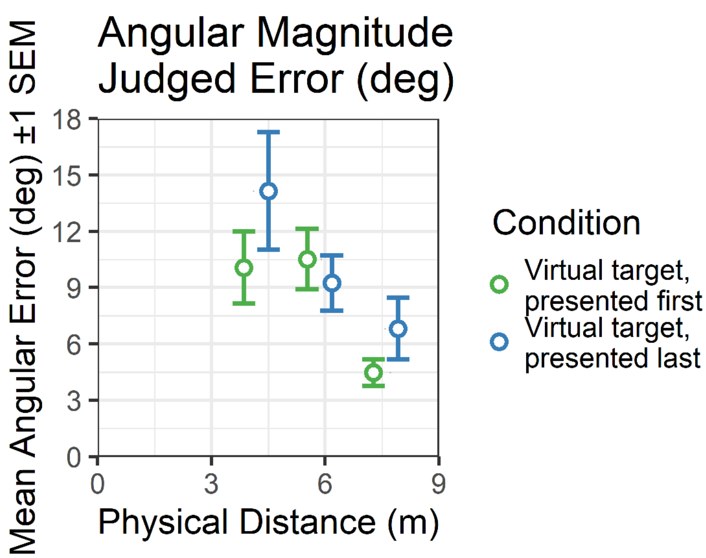


Figure 8.14: Experiment 3 angular error magnitude with confusion distances ($N = 15$). Note that the distances at 4.18, 5.85, and 7.59 meters are the normal test distances (in green) that were repeated multiple times per experiment, while the confusion distances were intermittent distractors (in blue), with only a few presented per experiment.

In Experiment 3, there was, surprisingly, a main effect of distance on the magnitude of the angular error ($F_{(1.31,18.4)} = 7.9$, $p < .01$, η^2 = .21 [large effect size]), as measured by ANOVA tests. Note that, because Mauchly's test of sphericity was significant at $p > .05$, this result has been modified by Greenhouse-Geisser correction. This effect, seen in Figure 8.12, shows angular error decreasing with distance. This was not observed in Experiment 2 or in previous research on medium-field depth perception [8, 43] and so may be related to the presence of the new factors introduced in Experiment 3, namely the HMD and the window and wall paradigm. In consideration



(a) Real target $(N = 8; N = 7)$



(b) Virtual target $(N = 7; N = 8)$

Figure 8.15: A comparison of angular error magnitude in Experiment 3 $(N = 15)$, split between participants who experienced the condition first and participants who experienced it last. Left/right displacement of the conditions is for visual clarity and does not represent any difference in distance.

of the novelty of the window and wall paradigm within experimental research, this seems like a particularly promising source for this observed effect. Further data related to the window and wall paradigm is available in the Experiment 4 results below and is discussed in Chapter 9.

Outliers In Experiment 3, no outliers were observed (based on the 50° threshold). An outlier nearly rose to the cutoff threshold (Table D.1 in Appendix C) at 48.96° of underestimation; however, the error magnitude drops off quickly beyond that.

8.3.4 Experiment 4

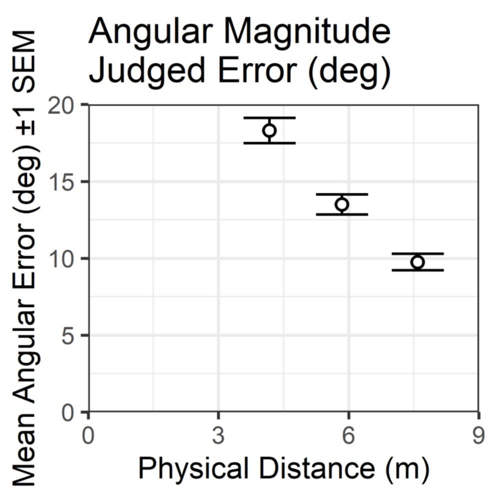


Figure 8.16: Experiment 4 angular error magnitude ($N = 20$).

In Experiment 4, participants walked to targets in a flat, enclosed indoor environment, with target distances of 3.66, 5.49, and 7.32 meters. In this experiment, participants wore an HMD and judged the distance to virtual targets in different **viewing conditions**. These conditions each modified the participant view of the target in unique ways and included the real window condition, the virtual window condition, and the opaque wall condition. Results are presented in Figure 8.16 in terms of angular error. Results are further presented by condition in Figure 8.17.

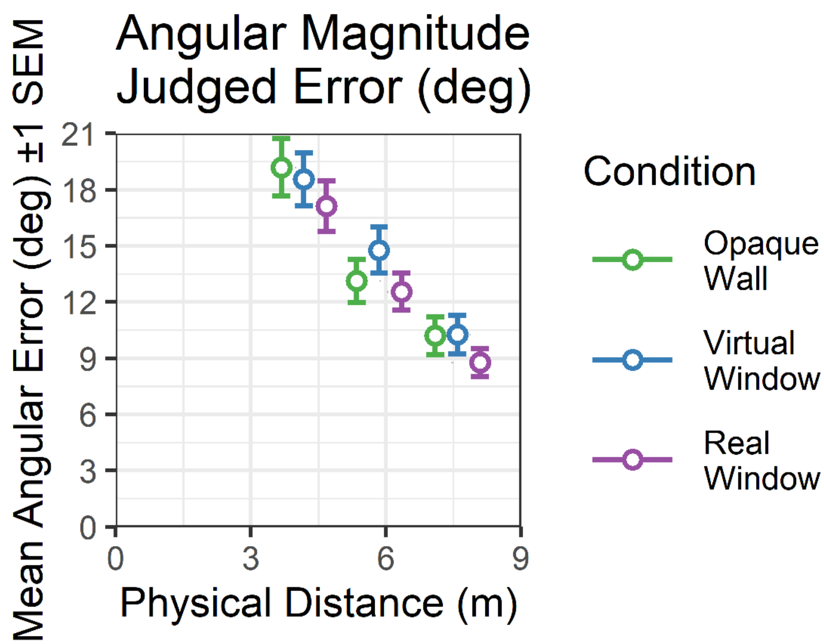


Figure 8.17: Experiment 4 angular error magnitude by condition $(N = 20)$. Left/right displacement of the conditions is for visual clarity and does not represent any difference in distance.

H4.1, the first hypothesis for Experiment 4, was that the presence of the opaque wall would have a significant negative effect on perceived object location as compared to the virtual and real window viewing conditions. Using ANOVA tests, no significant effect of the opaque wall was found, either in comparison to the virtual window $(F < 1)$ or the real window ($F_{(1,19)} = 1.1, p > .05$).

H4.2, the second hypothesis for Experiment 4, was that the presence of the virtual window would have a significant negative effect relative to the real window condition. Using ANOVA tests, no significant difference was found between the virtual window and the real window ($F_{(1,19)} = 1.7, p > .05$).

With the meaningfulness of these results, it is helpful to analyze them in further depth. As such, a general linear model is created and used to evaluate this set of hypotheses. For H4.1, no significant effect was found, either in comparing the opaque wall with the real window ($F_{(1,14)} = 1.9, p > .05$) or with the virtual window ($F < 1$). For H4.2, a significant difference is found between the real-world window and the virtual window ($F_{(1,19)} = 7.1, p < .05$, $\eta^2 = .27$ [large effect size]). Even though the initial analyses suggested that there was no significant difference between the real and virtual windows, the general linear model does show significance. This would suggest that the virtual window had an overall negative effect on participant judgments, as compared to judgments through a real window.

In Experiment 4, the main effect of distance on the magnitude of the angular error continued to be observed ($F_{(1.48,28.04)} = 21$, $p < .0001$, η^2 = .237 [large effect size]), as evaluated by ANOVA tests. Note that, because Mauchly's test of sphericity was significant at $p > .05$, this result has been modified by Greenhouse-Geisser correction. Once again, this effect, seen in Figures 8.16 and 8.17, shows angular error decreasing with increasing distance. With this result, Experiment 3 and Experiment 4 both demonstrate this effect across all conditions tested, demonstrating increased certainty in the result. The potential reasons for this effect will be discussed further in Chapter 9.

As in Experiment 3, a potential confound within this experiment is participant memorization and training effects. With modified experimental conditions and length, it would be possible for Experiment 4 to exhibit memorization effects, regardless of the results from Experiment 3. In order to visualize this potential effect, the confusion distances and regular distances are presented together in Figure 8.18. Visually, no clear pattern can be seen from the presented data.

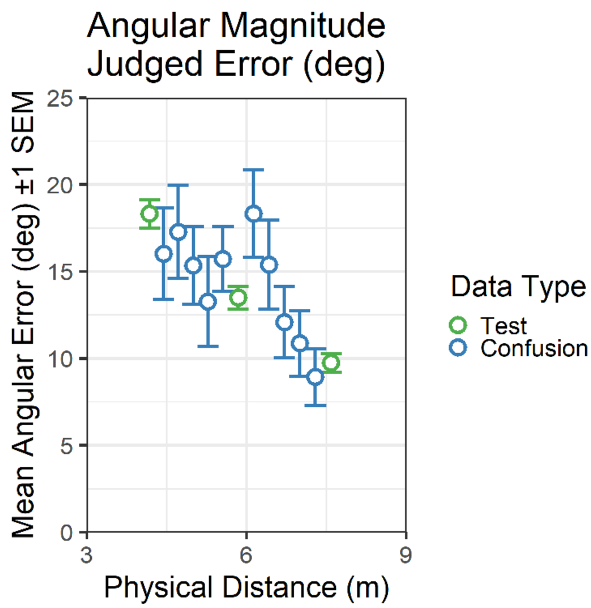


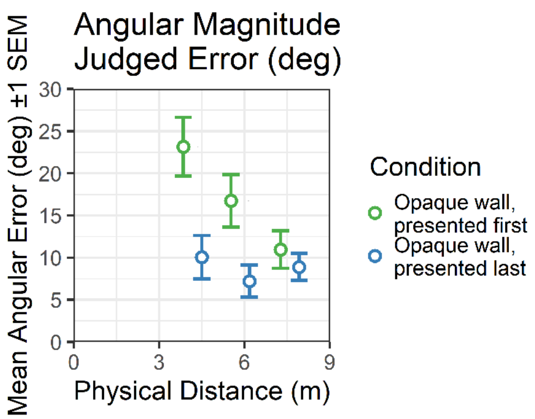
Figure 8.18: Experiment 4 angular error magnitude with confusion distances $(N = 20)$. Note that the distances at 4.18, 5.85, and 7.59 meters are the normal test distances (in green) that were repeated multiple times per experiment, while the confusion distances were intermittent distractors (in blue), with only a few presented per experiment.

A second major potential confound is the possibility of training effects. Particularly for Experiment 4, the order in which participants experience the conditions could be significant. The real window condition seems like it might initially supply the participant with more information as compared to the opaque wall or virtual window conditions, and it is possible that this could effect experimental results. In order to visualize this potential effect, both conditions are displayed in Figure 8.19, with participants split into a group where that condition was presented first and one where that condition was presented last. This data suggests that condition ordering may have a significant effect on participant depth estimations in Experiment 4. It is not fully clear how these effects would play out in the data, but there seem to be clear and distinct differences between participant performance in some conditions presented first in the condition order and the same conditions presented last in the condition order. This will be discussed further in Chapter 9.

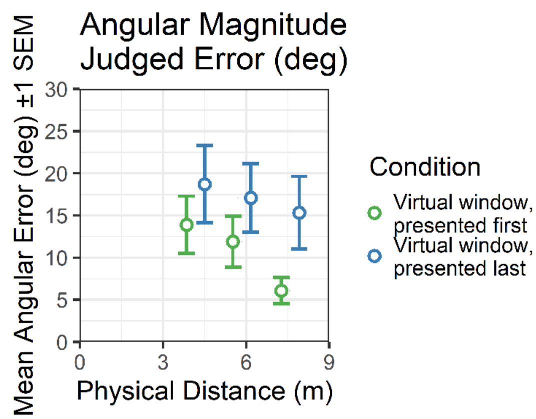
Outliers In Experiment 4, there were an unusually large number of outliers, with nine trials with over 50° of error (Table D.1 in Appendix C). These trials were spread out across three participants, with several more outliers just under the cutoff point. For four of these errors, a simple solution of replacing the aberrant stop point with the participant's other recorded trial (for the same condition/direction/distance) was deployed. A fifth trial required an adjustment to the participant turning point as well. Finally, the last four errors all come from the same participant across two conditions and necessitated replacing their aberrant judgments with a walking path averaged out from the other participants. In addition to these issues, there was also a procedural error which required a simple correction to two turn points. Experiment 4 required the most extensive outlier modification; these outliers stand out amongst the full set of experiments.

8.4 Summary

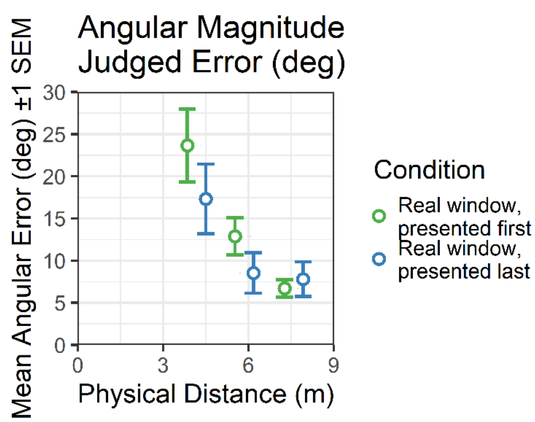
In this chapter, the data analysis and results were set up and introduced. First, the three data analysis methods used in this research, left/right intersection, origin intersection, and angular error, were evaluated. Of the three, angular error was chosen as the most effective and descriptive approach for the experimental tasks presented in this research. The experimental results for all four experiments were also introduced and the hypothesis tests presented. The triangulation by walking task from Fukusima et al. [33] was conceptually replicated in Experiment 1, with agreement between the results and Fukusima et al.'s original results. In Experiment 2, this was extended to an indoor environment, the results of which did not agree with Fukusima et al.'s findings. Further,



(a) Opaque wall $(N = 6; N = 7)$



(b) Virtual window $(N = 6; N = 7)$



(c) Real window $(N = 8; N = 6)$

Figure 8.19: A comparison of angular error magnitude $(N = 20)$, split between when the condition was first presented and when it was last presented. Left/right displacement of the conditions is for visual clarity and does not represent any difference in distance.

noise cues were examined in Experiment 2, and no significant effect was found. In Experiment 3, the effect of object virtuality was examined and found to be not significant. Memorization and ordering effects were also considered, but no clear trends were visible. In Experiment 4, viewing condition was examined, and judgments made through a real window and an opaque wall were found to not be significantly different. Using a general linear model, a statistically significant difference was found between judgments made through a virtual window and judgments made through a real window. This is in contrast to the ANOVA testing that found no significant effect of the virtual window on angular error. Memorization and ordering effects were examined for Experiment 4, and some visible effects were observed. Finally, in contrast to Experiments 1 and 2, a significant finding of decreasing angular error with respect to increasing distance was observed in Experiments 3 and 4. This effect appears novel to this research and may be related to the wall and window paradigm. These results set the stage for Chapter 9, in which further discussion and analysis is performed.

CHAPTER IX

DISCUSSION

In order to fully consider the importance and findings of this research and connect these findings to the main research question presented in Chapter 1, it is important to discuss the results from Experiments 1 through 4 presented in Chapter 8. These results are grouped by experiment, discussing the hypothesis results along with other notable findings. Finally, the last section details how these results build toward answering the main research question for this work,**"Can a real window be replaced with an AR window?"**

9.1 Experiment 1

In Experiment 1, RQ1 was asked, **"With what certainty can the triangulation by walking method presented by Fukusima et al. [33] be conceptually replicated?"** Such a result would both reinforce Fukusima et al.'s original findings of veridicial depth estimation using triangulation by walking outdoors at medium field distances and validate the experimental methodology used in this research. The initial hypothesis was that the results of Experiment 1 would agree with the results of Fukusima et al.'s Experiment 4, as assessed by a visual comparison of results (Figure 8.8). Based on this comparison, Experiment 1 is a successful conceptual replication of Fukusima et al.'s Experiment 4 and the evidence from Experiment 1 supports H1.

This finding suggests that the changes made to Fukusima et al.'s [33] original methodology are sound and do not disrupt or modify participant location judgments relative to Fukusima et al. Further, this suggests that the distances tested in Experiment 1 (six, nine, and twelve meters) follow the same distribution as Fukusima et al.'s distances of six, twelve, eighteen, and twenty-four meters. This supports the use of the modified triangulation by walking methodology across other experiments in this and future research.

Beyond this, the results from Experiment 1 support several unique contributions. First, it provides additional evidence of general veridical depth perception outdoors at medium-field distances. It also shows additional evidence that triangulation by walking is a valid experimental task for evaluating perceived object location and depth perception at medium-field distances. However, at the same time, this research also calls into question the use of the left/right intersection methodology as a metric for measuring perceived object location and perceived depth. This method has provided useful results in Experiment 1 and in Fukusima et al.'s results [33], but it suffers from several issues, including geometrically scaling error rates, procedural issues, artificial error amelioration, and halving of available trial data. The origin intersection method, while no longer artificially reducing error or halving available trial data, still suffers from some of the procedural issues and geometric scaling issues that plague the left/right intersection method. As such, angular error was investigated as a potential solution–it is linear with respect to user error and avoids the other pitfalls of the left/right intersection method and the origin intersection method. For this reason, the angular error approach was chosen over the other options in subsequent experiments.

9.2 Experiment 2

In Experiment 2, RQ2.1 was asked, **"With what certainty can the triangulation by walking method presented by Fukusima et al. [33] be conceptually replicated indoors?"** Experiment 1 showed a conceptual replication of Fukusima et al. outdoors; did the indoor environment or the shorter target distances (3.66, 5.49, and 7.32 meters) modify perceived location? The initial hypothesis, H2.1, was that the results of Experiment 2 would agree with the results of Fukusima et al.'s Experiment 4 and show veridical depth perception through triangulation by walking tasks in an indoor environment, as assessed by a visual comparison (Figure 8.11). As can be seen in this figure, the left/right intersection method does not seem to represent a fully descriptive estimate of perceived location; indeed, it seems clear that participants did not estimate the target to be over 30 meters away on average. This figure is particularly helpful in visualizing some of the issues with using the left/right intersection method. Instead, going forward, angular error is the analysis methodology that seems most applicable to this set of experiments (Figure 8.9b). Based on the comparison in Figure 8.11, Experiment 2 does not appear to be a successful conceptual replication of Fukusima et al.'s Experiment 4, and this evidence does not support H2.1.

This suggests that the indoor environment or the modified target distances may have had a significant impact on perceived location, as those are the two main changes introduced in Experiment 2. Both were significant changes; however, it seems likely that the indoor environment was primarily responsible for the observed differences between the results of Experiment 1 and Experiment 2. The distances tested were not the same as in Experiment 1, but they were on the low end of what was tested. It seems unlikely that the changed distances would be significant, especially as each tested distance is within the medium field, where similar processes and depth cues are used [23]. In contrast, there are a number of possible reasons the indoor environment could modify participant perceived object location and several works indicating that environment has a significant effect on depth perception and perceived object location [56, 86, 2, 98]. In several of these papers, it has been shown that participants' depth judgments are strongly influenced by boundary conditions in an environment [98, 56]. Since participants were interacting with parts of the room near boundaries, both at the turn points and at the 7.32 meter far distance, it seems reasonable that these could easily effect perceived object location. Based on this evidence, it seems likely that the indoor environment had a significant impact on perceived object location in Experiment 2.

A second question, RQ2.2, was also asked, **"To what extent do noise cues influence participant's depth perception judgments?"** This question is important for methodological reasons and to better understand how participants navigate in a triangulation by walking task. The initial hypothesis, H2.2, was "Noise cues will not have a significant effect on perceived object location." Noise cues were present in both the outdoor condition of Experiment 1 and the indoor condition of Experiment 2, though they may have been more prominent in the confined, close-in environment of Experiment 2. This condition was inspired by feedback from a participant noting that they tried to use the position of the experimenter's voice to get a positional estimate of where they were when they were being instructed to turn toward the target (Appendix B, Experiment 2). This feedback, though subtle and prone to being mis-applied, could confound and modify participant's sense of self-location, and thus modify their perceived distance estimates. Through a series of ANOVA tests, no significant effect of the noise cue was found; this can be seen visually in Figure 8.10. Past research has also found no significance of noise cues on participant depth perception [33].

However, even though noise cues have not been found to have a significant effect, Experiments 3 and 4 were still performed with the experimenter not in the room.

Several relevant research contributions are supported by Experiment 2. First, the results from this experiment contribute to the growing body of research that indicates that environmental context is important to depth perception, even when depth judgments are taken entirely in the real world [56, 86, 2, 98]. This is particularly important for AR research, as much previous research takes place across a wide array of differing environments. This finding suggests the importance of validating participant depth judgments with similar task outside of AR before investigating AR-specific experimental questions. Without this step, it becomes difficult to tease apart the effects of the real-world environment from the effects of AR interventions and visualizations. Additionally, this experiment continues to demonstrate the usefulness of the angular error method for triangulation by walking, as compared to the left/right intersection method or the origin intersection method.

9.3 Experiment 3

In Experiment 3, RQ3 was asked, **"What is the effect of object virtuality on perceived object location when the target is viewed through a window?"** Previous research has generally found significant underestimation effects in AR [90, 47, 85, 37, 63]. Thus, the initial hypothesis, H3, was that object virtuality would have a significant negative effect on perceived object location. However, in actuality, no significant difference was observed between conditions in Experiment 3, as evaluated by ANOVA tests and a general linear model and demonstrated in Figure 8.13. This is a surprising finding, as previous research has largely found distance misestimation in AR [90, 47, 85, 37, 63] as compared to the real world. There are some research observations that go against this grain [89], but overall distance misestimation has been the norm in AR depth perception research.

While it is true that AR is usually less accurate than real-world vision, there are some important precursor discussions to have before returning to H3. For one, as seen in Figure 8.12 and 8.13, there is a further unexpected result across both conditions; as distance increases, the magnitude of the angular error decreases (a result also present in Experiment 4). This is unusual as the research shows generally consistent angular error within medium-field egocentric depth perception [92, 66, 98, 67, 96]. Perceived distances and variability may change with distance, but the overall angular error tends to remain static, given normal cue conditions. As such, angular error that changes with distance stands in contrast to the previous research, as well as to Experiments 1 and 2. There are two main factors which were changed between Experiment 2 and Experiment 3 that could potentially explain these unexpected results, namely the presence of the wall and the effect of wearing the Magic Leap One HMD. Other than these variables and some minor procedural changes, the environment, methodology, and approach remained the same as in Experiment 2.

It has been shown that wearing an HMD or carrying a heavy backpack is related to modified depth perception judgments [96, 80, 51]; it is important to evaluate whether such an effect might cause angular error to vary with distance. The research shows that the effect of wearing an HMD may be due to the effort expected by participants during a walking task, a more limited field of view (FOV), HMD weight or resolution, or even some perturbation of the body's physical center of balance [51, 96, 80, 46, 21]. In VR, these effects seem to result in a pronounced difference between depth judgments made in older displays, as compared to more modern displays (Figure 9.1). It is possible, in particular, that the weight, FOV, and ergonomic form factor of modern devices is a

Fig. 2: Forest plot showing individual means and 95% CI for all studies included in the meta-analysis. Labels on the left indicate the HMD used in each study. Data are sorted by the year in which the HMD was first produced (not shown). The vertical line at 1.0 represents perfect performance.

Figure 9.1: An overview of measured depth perception judgments through VR displays over time. The y-axis represents display age and the vertical line at 1.0 veridicial depth judgment. Note the increasing accuracy of VR depth judgments over time. Graph by Jonathan W. Kelly [51].

significant driver of this effect [96, 46, 51]. Indeed, the Magic Leap One headset, like the HMD from Willemsen et al. [96], does constrain FOV–a factor that has been thought to have an effect on egocentric depth perception. However, in contrast, the Magic Leap One headset (316 grams) is much lighter than a backpack or the cited display (1050 grams) and is also significantly more modern, comfortable, and ergonomic than previous designs (Figure 9.2). These factors have been associated with more accurate depth perception in VR, where distance estimation has historically suffered from depth misestimation [51].

(a) The NVIS HMD.

(b) The Magic Leap One.

Figure 9.2: The NVIS display (1050 grams) as compared to the Magic Leap One (316 grams). Note that both displays have wires attached to the headset.

Further, the depth misestimations that have been attributed to HMDs have been characterized by a consistent angular error within a given experiment [51, 96, 80, 46, 21]; each experiment may find a differing degree of error, but that error rate tends to be consistent within experiments. As such, it is unlikely that the HMD is responsible for the relationship between angular error and distance. An HMD might introduce a change in angular error, but that change would likely be consistent across distances; this does not fit the pattern observed in Experiment 3 and so it is unlikely that the HMD is the cause of the relationship between angular error and distance.

The relationship between angular error and distance might also be explained by the wall and window paradigm introduced in Experiment 3. This paradigm encompasses all the unique changes caused by viewing the target through a window in a wall. The effect of introducing this window and wall paradigm is likely fairly complex and has not, to the author's knowledge, been previously studied in the research, so it represents a promising explanation for the observed effect of distance on angular error.

On the one hand, the presence of a wall might present to participants as a source of extra work, which could very easily cause participants to judge distance as farther away, particularly for a walking task [59, 80, 97, 96]. Viewing targets through a window could also bias depth judgments if the wall is seen as a boundary or environmental anomaly. In previous research, even distinctions as simple as differing types of ground textures have been found to bias depth estimates, so it seems reasonable to conclude that a wall certainly could have that potential [56, 86, 98]. However, the pattern observed here does not seem to fully fit the models previous research established for texture or work effects. If participants were viewing the wall as a source of extra work, why was the magnitude of turning error reduced at farther distances? This implies that the observed effects of the window and wall paradigm are not significantly driven by the ground texture or any perceived additional work associated with the wall.

Instead, the strongest explanation of the observed effect of the window and wall paradigm may be related to environment segmentation and cognitive maps. The segmentation of the environment is important in depth perception; various types of boundaries, obstacles, and apertures have been studied in previous depth perception research [86, 95, 98, 56]. This area of depth perception has several different active research areas, including gap and cliff judgments [86], passability measures [95], and border boundary conditions [98, 56]. Of these, gap and cliff judgments follow a pattern of a consistent angular error misestimation while the observed effect in this work involves decreasing angular error over increasing target distance [86]. Passability measures also do not seem to readily apply in this context. It is unclear how border boundary conditions might effect participant depth judgments–unlike the cited research, participants navigated around the wall without ever intersecting with it. It is possible that avoidance or perceptual awareness of the wall caused participants to subtly alter their depth judgments or alter course to avoid the wall. This may have been more pronounced at closer distances where participants were necessarily walking closer to the wall, resulting in higher angular error at nearer distances. Such an explanation seems reasonable and sound but requires further elaboration and evidence before being fully accepted

The answers to these questions are not fully understood with this research–further investigation is necessary to fully understand the source of the observed change in angular error with distance and further define its relationship to the wall with a window paradigm. Testing perceived object location through a wall with a window is, as far as can be determined, unique to this work and so this result is novel and as yet unexplained. For this reason, it seems likely that the observed changes in perceived object location are driven primarily by the presence of the wall and window paradigm but may be influenced by participant use of the HMD.

With this context in mind, it is instructive to consider other possible reasons why the data did not support H3. The virtuality of the displayed object was not found to be significant, which is a surprising, but not unprecedented, result across AR research [56, 86, 98, 89]. Still, this result raises a natural question as to why virtuality was not significant in this experiment. One possibility, as discussed earlier, is that improvements in HMDs have reduced the effect of object virtuality on perceived object location. This seems like it may have contributed to the lack of significant findings related to object virtuality by reducing the size of the effect but may not be the full picture. In some previous research where HMD usage has been analyzed, a significant effect of object virtuality was still found, even when the physical weight and form factor of the HMD itself were factored out [96]. Another question that could be asked is whether the significance of the window and wall paradigm might override any significant effect of object virtuality. The error introduced by virtuality might have been hidden by a stronger, more salient effect, in essence drowning out the signal of object virtuality in the noise of the relationship between angular error and distance. This seems like a reasonable conjecture but is not fully explanatory. The effect observed between angular error and distance is notable, but a strong effect of object virtuality would still be visible even against this backdrop. This suggests that the effect of object virtuality is marginal at best and so downplays the significance of any overriding effects from the angular error effect. Two other factors that might bias results include condition ordering and memorization [99, 30]. However, neither Figure 8.14 or Figure 8.15 seem to illustrate a clear pattern of bias or memorization in the result. As such, it seems likely that the lack of significant effect of object virtuality observed in Experiment 3 is reflective of the nature of the experimental task and protocol. Factors such as object virtuality and the window and wall paradigm might contribute to these findings but do not seem to explain them.

Several important and interconnected research contributions are supported by Experiment 3. First, the results from this experiment contribute to research related to AR depth perception in the medium field, a small, but important field [89, 90, 61, 85, 37]. Even further, this research evaluates a novel paradigm for depth perception research: that of position and depth judgments made through a window in a wall. This has not been tested previously in a real-world environment, much less AR. Testing this new paradigm has revealed an apparent effect of the wall on depth perception that has not been previously discovered. This knowledge contributes both to the scientific understanding of general perception and relates, more specifically, to how x-ray vision depth perception might be understood, perceptually. Finally, this research also implies that AR and object virtuality, when used with modern HMDs, may not necessarily have a significant negative impact on perceived object location as has been previously understood, though further research is warranted here.

9.4 Experiment 4

In Experiment 4, RQ4.1 was asked, **"What is the effect of a fully opaque wall on perceived object location?"** Previous research has generally shown that depth perception to targets presented through an opaque wall is less effective than depth judgments to targets seen without obstruction, an effect often attributed to the occlusion cue conflicting with other presented visual cues [9, 65, 34]. This has been seen in previous research [34], but results related to this are sparse in the medium field. A second question, RQ4.2, was also asked, **"What is the effect of a virtual window and frame against an opaque wall on perceived object location?"** Previous research has shown virtual window techniques to be effective at improving depth perception judgments [34], but these findings also seem to show that depth perception through this virtual window is still not the equivalent of real-world unconstrained depth perception. Thus, the first hypothesis, H4.1, was that the presence of the opaque wall would have a significant negative effect on perceived object location as compared to the virtual and real window conditions. The second hypothesis, H4.2, was similar: "The virtual window and frame will have a significant negative effect relative to the real window condition." Together, these two hypotheses encompass the three different comparisons possible between conditions. However, no significant difference was observed between conditions in the opaque wall and real window conditions, as evaluated by ANOVA tests and demonstrated in Figure 8.17. As such, these results fail to support H4.1. On the other hand, a significant difference was found between the real and virtual window condition as assessed by a general linear model. This finding, accompanied by the graphs related to this result (Figure 9.3) implies that the virtual window condition actually performed more poorly than the opaque wall condition, as compared to depth perception through the real window. This result supports H4.2. This set of results is in contrast with previous research [34], and it is important to consider and evaluate possible reasons for this result.

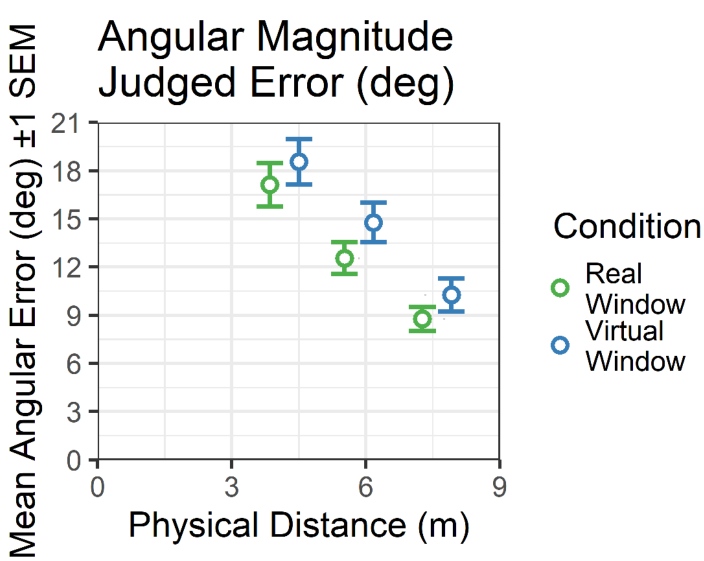


Figure 9.3: Experiment 4 angular error magnitude, modified from Figure 8.17, comparing the real and virtual window conditions $(N = 20)$. Left/right displacement of the conditions is for visual clarity and does not represent any difference in distance.

To fully evaluate the results from H4.1, it is important to consider several different factors. First, a major trend from Experiment 3 continues to be relevant in Experiment 4. The observed effect of decreasing angular error with increasing target distance continues to be significant in this experiment. Some possible reasons for this result are discussed in Chapter 9, Section 3 above, but the window and wall paradigm is expected to be a primary driver of this effect. In terms of effect size, this result is quite large, with an η^2 of .237. It is natural with such a large effect to wonder if it could potentially overwhelm any potential effects viewing condition might have on perceived object location. However, if the misestimation caused by viewing condition is in line with previous research, it would be expected to see depth misestimations of over a meter, a result which would be significant even in conjunction with the large effect of distance on angular error. That such an effect is not observed seems to strongly support there being no additional effect of the opaque wall condition on perceived object location.

However, there are two primary considerations intertwined with this finding. The first is relatively straightforward; it should be evaluated how Furmanski et al.'s finding of over one meter of depth perception error [34] relates to the findings of Experiment 4. On the surface, this does not seem to agree with the findings from Experiment 4, but it might be the case that Furmanski et al.'s findings might actually be a measurement of the relationship between distance and angular error seen here. If angular error decreases with distance in the window and wall paradigm, it is possible that Furmanski et al. measured this effect and attributed it specifically to vision through an opaque wall. After all, the closest ecologically valid context for vision through an opaque wall is viewing an object through a window, so it seems reasonable that Furmanski et al.'s results might reflect the effect observed in Experiment 4.

In evaluating Furmanski et al.'s results [34] in conjunction with Experiment 4's finding of increasing angular error with respect to distance, it is important to consider some intervening factors that complicate the relationship between the two findings. First, it is difficult to fully evaluate the effects seen in Furmanski et al., as only one target distance was judged, forced choice feedback was used, and older technology was used. In particular, the lack of continuous participant feedback and the single tested distance makes it difficult to generalize the findings from Furmanski et al. With only one data point available for comparison and no validation to real targets, no significant judgments can be fully drawn. Further, Furmanski et al. uses an older, heavier HMD, which may have a measurable impact on participant depth judgments. As such, it is difficult to draw conclusions from Furmanski et al.'s work, but it may be representative of the interaction between angular error and distance observed here. This conjecture may explain Furmanski et al.'s original findings but does not shed much light on the lack of significant difference between the opaque wall and real window conditions.

A second set of factors related to H4.1 is the order in which conditions are presented and participant memorization of distances, both of which are experimental issues that have been discussed in previous research [99, 30]. It has been thought that the condition shown first in an experiment has a potentially significant impact on judgments made in later conditions [99]. While the presentation order of conditions in this experiment was counter-balanced with a Latin Square [10] such that ordering effects should be averaged out in the results, it is still possible that condition ordering biases the results, both in terms of practice effects, where judgments might slowly improve across the experiment, and in terms of learning and memorization, where judgments in later conditions are influenced by the results from previous conditions. For this experiment, the latter seems especially likely as certain conditions may be advantaged with respect to others; it seems reasonable that participants might learn the target distances from the real window condition and use that knowledge in the virtual window and opaque wall conditions. Indeed, there appears to be some validity to these concerns; Figure 8.19 shows the difference in mean depth estimations made in the first trial of each condition as compared to mean depth estimations made in the last trial of each condition. The pattern revealed in this figure is not conclusive, but showcases the importance of condition ordering as a notable concern for this experiment.

A visual look at the potential effects of memorization are illustrated in Figure 8.18. This figure, which shows both the primary tested distances together with the confusion distances, visually illustrates patterns related to learning and memorization. While no reasonable significant results are available from this data (as each confusion distance was only tested in some experiments), it illustrates a spread of values that seems indicative of unique depth judgments at each presented distance, as opposed to participants acting off a memorized set of percepts for the main tested distances. This seems to suggest that memorization isn't a major factor in the experiment.

In essence, then, the lack of observed effect for the opaque wall condition was a significant finding with importance to the larger field of AR research and application development. This finding opens up the possibility of x-ray vision applications that are comparable to looking through a physical window. However, this finding is in contrast to the limited previous work done on medium-field x-ray vision [34] and seems to exhibit some evidence of learning effects. This is an important finding for the field and further research should be done to more fully understand and explore this effect.

Past these findings, it is also important to discuss the findings from H4.2, where a significant negative effect of the virtual window was found with respect to the real window (and where no significant effect was found between the opaque wall and virtual window conditions). This effect is interesting, as it is precisely the opposite of what previous research has predicted [9, 34, 65]. However, participant feedback during the experiment was consistently that the virtual window made depth and location estimations more difficult and harder to detect (Appendix B, Experiment 4). Certain participants mentioned that the window's black background was unintuitive and not what they associated with windowed viewing. Others more generally commented that the virtual window made them feel more uncertain or confused when viewing the target, even in comparison to the opaque wall condition. From this description, it seems like the virtual window was more of a liability than a visualization aid. From this feedback, it seems that visualization factors and expectations had more to do with the significant negative effect of the virtual window, as compared to the real window, on perceived object location.

The contributions from Experiment 4 are, in many ways, the highlight and focus of this work. As in Experiment 3, this experiment extends AR depth perception work in the medium field and investigates a completely novel paradigm with windowed object viewing. Once more, the window and wall seem to have a significant and previously unstudied effect on angular error, the nature of which requires additional study. Even past these important findings, however, Experiment 4 contributes results that are particularly important and striking in the field of AR and particularly x-ray vision. In the past, x-ray vision has been experimentally tested for depth effects only rarely, with the tests used being forced choice [34]. This didn't allow for a full mapping of participant understanding and didn't provide continuous numeric results. This research, then, both adds to that experimental record and exceeds it. Participant depth judgments to x-ray vision stimuli are measured, for the first time, using the visually directed action of triangulation by walking with validated methodology (see Experiment 1). This method produces an unconstrained, continuous depth estimate from participants, allowing for specific trends in depth estimates to be seen. In addition, this work supports the additional contribution of comparing three different target viewing conditions: viewing the target through a real window, viewing the target through a virtual window against an opaque wall, and viewing the target through a fully opaque wall. In the past, no corresponding comparison has been made in the context of viewing a target through any type of window in a wall. Further, the findings of this study (that is, that viewing an object through an opaque wall is not significant for participant depth estimates and that the virtual window can significantly hamper perceived object location) are important results that are central to the field of AR application development, as well as AR x-ray vision and depth perception research.

9.5 The Main Hypothesis

The central goal of this research was to answer the main research question, "Can a real window be replaced with an AR window?" It was predicted, in the main hypothesis, that a real window could not be replaced with an AR window without some loss of perceptual acuity and accuracy. This hypothesis is supported by the experimental data–however, the data also shows that a real window can be fully replaced with x-ray vision through an opaque wall with no significant loss of perceptual accuracy! These results are in contrast to previous research, which has found significant depth misestimations to targets presented past an opaque surface [34, 61] and a general positive effect of the window metaphor/virtual window [9, 34, 65]. As such, these findings are notable in the field and should be carefully replicated and extended in future experiments.

It was previously understood that there was a trade-off in medium-field AR, particularly as relates to x-ray vision. It was thought that x-ray vision could provide additional visual information to operators or application users, but at a significant perceptual cost; the objects that operators interacted with would have depth offsets and would not match the intended target locations. This understanding is supported by relatively few experimental results, and AR x-ray vision remains poorly understood. This is important as many AR applications require a high level of depth fidelity to be usable. This finding of usable x-ray vision through an opaque wall opens the door for application development of x-ray vision technologies; now, with the understanding that x-ray vision can produce depth judgments not significantly different than those made through a real window, the potential use cases for x-ray vision expands notably. Even though viewing an object through a virtual window was found to significantly hamper depth perception, the ability to accurately judge location in the opaque wall condition is of great utility for x-ray vision applications. This finding extends the field of AR x-ray vision, opens novel opportunities for application development, and supports the institutions and groups currently evaluating the potential usefulness of x-ray vision.

9.6 Limitations

This research and these findings extend the scientific understanding of AR x-ray vision. However, importantly, these findings also have several limitations and potential confounding factors that are important to fully consider and evaluate. For one, all the AR and windowed viewing experiments took place within a single indoor environment. This was particularly key as the indoor environment introduced several constraints and boundaries to participants, which have been shown in the past to significantly effect depth perception [56, 86, 2, 98]. To counter these issues, an outdoor AR experiment was investigated, but implementation proved difficult; the virtual objects displayed by the HMD were faint and hard to see in the brightness of a sunny day. These considerations underscore the impact of the environment on participant depth judgments and demonstrate the need for experimentation in varied contexts.

Even further, this research uses only one OST AR HMD, and it is possible that the observed results could vary substantially when performed with other HMDs or visualization paradigms. This same critique can be applied to many different aspects of the experiments detailed here; this experiment supports only one window design, three different testing distances within the medium field, one window size, one target type, and one wall texture, and these features represent both notable limitations and areas where the research could be expanded.

This study is also limited with respect to sample size and so it would be useful to run more participants and produce results with higher confidence and greater power. This might allow different types of analyses to be run, with the potential for relationships between demographic or handedness data and depth perception to be explored, neither of which is currently addressed in this work. As is common with studies run at universities, this research predominantly features relatively young individuals (generally in the range of 18-25 years old) recruited while attending school. It is possible that depth perception judgments could be significantly different between age or demographic groups, and, as such, non-representative recruitment could have a significant effect on the observed results. It is possible, too, that experience in other AR or VR experiences or experiments may have had some manner of biasing effect on participants and thus may have modified the way in which they perceived or responded to the experiments. Additionally, ordering effects may have had a significant effect on the findings of these experiments (Figures 8.15 and 8.19), and memorization effects could also have played a significant role (Figures 8.14 and 8.18). This could serve to confound and modify the results presented in this research and so should be evaluated in further detail.

Finally, there remain potential limitations related specifically to viewing targets through the virtual window and opaque wall conditions. Primarily, the design of the virtual window itself seemed to be problematic; several participants reported difficulty in perceiving it as a window or understanding the depth of objects presented through it (Appendix B, Experiment 4). Even farther, no participant reported it as improving their depth perception understanding. The most positive response to the virtual window came from several participants who reported that it neither disrupted nor improved their performance. This feedback seems to indicate that the virtual window, in particular, was not in a form factor to which participants reacted favorably.

These considerations highlight the limitations of this work and define opportunities for further research efforts in this area. In order to best understand the contributions presented in this work, it is important to also consider the full context in which this research takes place. The contributions and opportunities of this work will be further discussed and highlighted in the next chapter, Conclusion and Future Works.

9.7 Summary

In this chapter, the findings presented in Chapter 8 were discussed and analyzed further. Potential reasons and confounds for the experimental results were discussed. Experiment 1 validated the experimental methodology by successfully conceptually replicating Fukusima et al. [33]. Depth perception findings also showed the importance of the analysis method and suggested a move toward angular error analysis. In Experiment 2, this effect was even more significant, further underscoring and supporting the move toward angular error analysis. Experiment 2 also demonstrated the importance of the indoor environment, by introducing boundary conditions. Noise cues were found to be not significant. In Experiment 3, the failure to find a significant effect of object virtuality was discussed, and some of the potential confounding factors, such as memorization, condition ordering, and the relationship between angular error and distance, were analyzed. It was determined that there was a lack of significance for the object virtuality condition. In addition, the effect of decreasing angular error with increasing distance was discussed, along with several potential reasons for this effect, including the boundary considerations related to the window and wall paradigm introduced in Experiment 3. In Experiment 4, it was found that the opaque wall and real window conditions were not significantly different, while the virtual and real window conditions were found to be significantly different using a general linear model. A significant factor in the latter effect may have been the design of the virtual window–participants reported that the virtual window was unintuitive and not suggestive of an actual window. The potential confound of learning effects is another important concern for these results; visual evidence is suggestive of participant learning that varies between conditions, particularly in the case of the opaque wall condition. This work had several additional limitations, including limited sample sizes, no evaluation of demographic data, and various environmental factors, among other issues related specifically to the windowed conditions. The results from Experiment 4 do support the main hypothesis (which is that a real window would allow for better depth perception than a virtual window), but these results also suggest that the opaque wall condition was not significantly different from the real window condition. This finding is significant and provides support for further AR x-ray vision research and application development.

CHAPTER X

CONCLUSIONS AND FUTURE WORK

In Chapter 9 the implication and meaning of the results from Experiments 1 through 4 are discussed and analyzed in some detail. In this chapter, this analysis is summarized, with a succinct description of the research findings and their significance. Further, avenues for extension or elaboration of this research are proposed.

10.1 Research Findings

This set of experiments was sufficient to answer the main research question, **"Can a real window be replaced with an AR window?"** The results from Experiment 4 support the finding that a real window can not be replaced with a virtual window without a significant loss of accuracy. However, these results also support the finding that a real window could be replaced with an AR overlay through an opaque wall with no significant loss of location or depth accuracy. This is significant both as a research finding and as a baseline for application development. In the past, research has shown significant depth misestimations when using x-ray vision through OST AR [34, 61]; a finding that AR x-ray vision can support vision comparable to a real window represents a notable change. Even farther, this finding underscores the usefulness of AR x-ray vision for certain application contexts. If x-ray vision is effective, usable, and mobile, it opens up application contexts across disaster reconnaissance, tactical operations, industry, and medical fields, in addition to its significant research implications.

Another major finding of this research is that the virtuality of objects presented to participants is not significant in perceived location judgments. There has been growing evidence that VR depth perception has been becoming more accurate with lighter, newer, and more powerful devices (Figure 9.1) [96, 51, 21, 52, 14], and this result emphasizes the effect of more modern HMDs. Such a trend may also be occurring in AR HMDs, as devices in this field are also becoming increasingly more powerful, light, and mobile. The lack of significance of object virtuality provides additional evidence that the foreshortening problem often observed in VR [96, 51] is not significant in modern medium-field AR. Even further, this research contributes evaluations of AR depth and location perception in the medium field. Thus, these results contribute to a small but growing body of research related to the well-known problem of depth misestimation in AR [89, 90, 61, 85, 37]. To fully understand AR depth perception, further research must be done, but this research represents an important step along the way.

Another contribution relates to the effectiveness of the window metaphor. In past research, the window metaphor in AR x-ray vision has been associated with increased accuracy for participant depth perception [34, 9, 65]. These findings, however, call that effect into question; the virtual window condition was significantly less accurate than the real window condition, thus significantly reducing depth and location judgment accuracy overall.

In addition, this research is the first to analyze the effect of viewing an object through a window in the real world on the perceived location of that object. Even aside from explicitly AR-based research, this represents a significant contribution to the field of perception and to scientific knowledge of human visual understanding. Related to this contribution, a surprising effect of judging distances through the wall was found; apparently, angular error to the target decreased with distance in all experiments in which the wall was present. The potential reasons for this effect are discussed in detail in the previous chapter, but, prior to this work, this effect has not been previously witnessed. This finding is both novel and significant to human depth perception research.

Further contributions include certain methodological advances. This research conceptually replicates a triangulation by walking procedure presented by Fukusima et al.[33] and provides further validation of its accuracy and usability. This modified approach is also detailed in this work, allowing for additional replications or evaluations using the modified triangulation by walking methodology. An examination of the potential confound of sound cues was performed and no significant effect was observed. Finally, this research also contributed an analysis of three separate ways of analyzing perceived object location and judged error: the left/right intersection, origin intersection, and angular error analysis approaches. The benefits and weaknesses of these methods were considered, and angular error was evaluated as the most effective method in this experimental context.

10.2 Future Work

In order to extend this work and address its limitations, several options exist, as discussed in Chapter 9.6. The most obvious and suggestive of these would be to replicate this methodology with more participants in a novel environment, especially a large, open environment. The AR and x-ray vision effects observed in this research were all evaluated in the context of depth judgments in a constrained space. The number of participants in this research was enough to establish sufficient power to evaluate the hypotheses, but it would be instructive to see a replication with a larger number of participants and, thus, higher experimental power. Further, if an experiment could be run outside, this would add valuable information and context to the results. This experiment could also be extended by including an evaluation of different HMDs, different types of wall textures or sizes, different target shapes and colors, and different window sizes. In particular, differing designs and configurations of the virtual window could be tested and experimentally evaluated. Finding a virtual window design that more successfully aids participant depth perception might notably change the results as related to the virtual window. It would further be useful to remove a potential confound by performing an experiment where the conditions vary between subjects; these results would avoid the pitfalls of participants applying learning from one condition to another condition.

In a different direction, understanding the effect of x-ray vision on participant cognition and situation awareness would be another research direction for this work. One approach to this might be to investigate the effect of x-ray vision on a participant's cognitive load. *Cognitive load*, also referred to as cognitive demand, is a measure of how much overhead a task or environment imposes on an operator's cognitive apparatus [73, 55]. This variable measures, broadly speaking, how hard an operator has to think to perform a task or operate within an environment. More fully understanding this component of x-ray vision could be important to understand how to best design AR applications and experiences.

Another important area that this approach doesn't directly address is the actual use of x-ray vision in situations such as disaster relief missions or training exercises. It is difficult to anticipate how a live response team equipped with the functional testbed version of this technology would perform in stressful or high-risk situations, and it would be important to find and incorporate personnel trained in the specific application task. The effect of practice and training with x-ray vision technologies would also be interesting to document and research. This research could also be related to situation awareness, with metrics that evaluated team members' effectiveness and response time in intense situations.

10.3 Summary

This research was designed to evaluate AR x-ray vision based on the nearest real-world analogue: vision through a window. Based on this approach, it was found that x-ray vision and vision through a real-world window were not significantly different, a surprising finding that suggests AR technology has the potential to be a key component in a wide set of solutions related to x-ray vision. Other significant findings include a significant effect of the window and wall paradigm on participant angular error, no significant effect of object virtuality on perceived object location, and several methodological advances. These results demonstrate the potential effectiveness of augmented reality to solve real-world problems and tangibly extend scientific knowledge related to perception and AR. It will be exciting to observe the AR research and development community as this potential is realized!

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APPENDIX A

GENERAL QUESTIONNAIRE

1. Gender:

2. Handedness:

3. Dominant Eye: Right Left Indeterminant

4. Date of Birth (mm/dd/yyyy): ________________

5. On average, how much time per week do you spend using a computer?

None less than 1 hr 1-4 hrs 5-10 hrs 11–20 hrs over 20 hrs

6. How many types of computer systems have you used (e.g., Mac, PC, Linux, etc.)?

None 1 2 3-4 5-6 more than 6

7. How often do you play computer games, from 1 to 7 (where 1 is never and 7 is very often)?

8. Please rate your ability to mentally visualize and manipulate shapes or objects, from 1 to 7 (where 1 is very poor and 7 is very excellent)?

9. Have you previously used virtual reality, augmented reality, or stereo glasses?

If yes, please note what you have used and how extensively.

male female

right left ambidextrous

yes no

10. Please estimate your uncorrected vision (your vision without wearing glasses or contacts):

worse than 20/20 20/20 better than 20/20

If you know it, what is your uncorrected vision (e.g. 20/20, etc.) : _______

11. Do you wear reading glasses?

If yes, do you wear them only reading or other close-up work?

12. Do you wear bifocal, trifocal, or verifocal lenses?

13. To the best of your knowledge, what is the power/prescription of your lenses?

14. To the best of your knowledge, do you have any color blindness?

If yes, please briefly describe which colors you cannot see.

15. To the best of your knowledge, have you ever had any problems with depth perception?

APPENDIX B

PARTICIPANT FEEDBACK

During Experiments 1 through 4 participants were debriefed at the end of the experiment. Participants were asked a set of questions, which included several free-response prompts. Some participants also behaved in non-standard ways or volunteered information even before the debriefing session began. All of these observations and responses are recorded here.

The debriefing questions included:

- Do you have any feedback on the experiment?
- Did you notice anything that seemed unusual or out of the ordinary?
- Did you use any particular strategies while performing the experimental task?
- Was there anything that distracted you during the experiment?

Experiment 1

- Subject 1
  - The participant noticed there were three target distances and tried to turn the same amount for each target.
  - The participant tried to remember where the target was while walking.
  - The participant closed their eyes and then turned toward the experimenter at the beginning of the experiment.
- Subject 2
  - Nothing unusual or distracting noted.
  - The participant reported thinking about the distance and the walk only.
  - The participant closed their eyes and then turned toward the experimenter at the beginning of the experiment.
- Subject 3
  - The participant lost their confidence while walking in the middle of the experiment and became unsure of where to stop.
  - There was noise near the experimental area (work trucks moving mulch into a trailer), mostly in the 2nd and 3rd repetitions. The participant mentioned that this was a distraction.

- Subject 4
  - No feedback given; no distractions.
- Subject 5
  - The participant did not notice anything unusual.
  - The participant only reported thinking about the target while walking.
- Subject 6
  - The participant did not notice anything unusual.
  - The participant only reported thinking about the target while walking.
- Subject 7
  - The participant did not notice anything unusual.
  - The participant thought about the turn they needed to take and the angles needed to be accurate.
- Subject 8
  - The participant figured out there were three different distances, and they turned least for the longest distance and turned most for the shortest distance.
- Subject 9
  - The participant did not find anything distracting.
  - The participant only reported thinking about the target while walking.
- Subject 10
  - The participant did not find anything distracting.
  - The participant pre-planned their turning angle before walking.
- Subject 11
  - The participant started to feel confident while walking as there was no feedback.
  - The participant reported thinking about the relative distance of the target.
  - A truck was there for work, and they found it distracting.
- Subject 12

- The participant did not find anything distracting.
- The participant only reported thinking about the target while walking.

- Subject 13
  - The participant did not find anything distracting.
  - The participant thought about the angle to turn such that they would face the target.
  - The participant noticed the tape marks for the targets.

Experiment 2

- Subject 14
  - The participant moved quickly in the last few trials and seemed confident.
  - The participant asked (after the experiment) about what the experiment was measuring and how accurate the results could be expected to be.
  - The participant's strategy was to mentally adjust their turning angle based on the observed distance.
  - The participant did not find anything distracting.
- Subject 15
  - The participant's strategy was to evaluate how far along on the path to the experimenter they were and to pre-compute that angle; for far targets, they turned less.
  - The participant did not find anything distracting.
- Subject 16
  - The participant did not have a specific strategy.
  - The participant was somewhat distracted by the room's sounds (primarily the loud air conditioning).
  - During a couple of early trials, the participant observed the experimenters measuring the turn and stop points before understanding that they needed to face the corner in between trials.
- Subject 17
  - The participant mostly walked along the wall, as opposed to directly toward the experimenter.
  - The participant said that they followed a linear path while walking.

- Subject 18
  - The participant mentioned that the location of the experimenter's voice could have affected their depth perception. (This was in the no headphones condition.)
  - Some of the way through the experiment, the participant noticed that the experimenter was moving in between issuing commands
  - The participant counted footsteps and evaluated their angular position occasionally (by turning their feet to align with the tile grid).
  - The participant counted around 5 footsteps to the turn point and 3-5 steps to the stop point.
  - The participant considered how much they moved (steps) when considering how much to turn.
  - The participant did not find anything distracting.
- Subject 19
  - The participant thought about the starting and ending point within the experiment; they estimated their stride length and thought about the angles needed to turn to the target. They observed that the turning angle would be small.
  - The participant did not find anything distracting.
- Subject 20
  - The participant thought about the patterns created by the starting point, turning point, and target in the experiment. They noticed the different lengths of triangles and wondered if they were equilateral in some cases.
  - The participant wondered how different shapes (for example, the square floor tiles, the cylindrical target, the triangular wooden door stop used as a marker to walk to.) affect perception.
  - The participant noticed the tiles were square; they didn't really use that, but evaluated it a little for squaring up.
  - The participant thought about the consistency of their steps.
  - The participant visualized a triangle while walking.
  - During the first few trials, the participant faced the target instead of the wood chip.
  - The participant clipped a wall column on one walk, but didn't seem bothered by the encounter.
  - The participant evaluated their walking pace during the experiment.
  - The participant did not find anything distracting.
- Subject 21

- The participant walked a curved path depending on the distance.
- The participant appeared to have some difficulties with imbalance while walking with their eyes closed. This seems to have been distracting, along with trying to trace the walked path while their eyes were closed.
- The participant would face the target, then close their eyes. They would then turn and walk a slightly curved path to the turning location.

• Subject 22

- The participant noticed that distances repeated often.
- The participant was a little distracted by thinking (they associated it with their ADHD).
- The participant had no particular strategies.
- The participant would face the target, then close their eyes and turn all in one motion.

• Subject 23

- The participant walked by the wall instead of straight to the wood block.
- In the debriefing, the participant mentioned that they weren't sure if they had to head to the wood block or along the wall.
- The participant did not find anything distracting.

• Subject 24

- Starting off, the participant felt off walking to the left.
- The participant did not find anything distracting. However, the experimenter noticed the participant tying their shoes a couple of times.
- Towards the end of the experiment, the participant rotated in place to generate a better depth understanding.

• Subject 25

- The participant did not find anything distracting.
- Participant mentioned using the sound of the air conditioning, which was consistently on, as a way to help them figure out their position.

Experiment 3

• Subject 26

- The participant mentioned feeling fatigued after the first half of the experiment.
- The participant did not find anything distracting.

  - By the end of the experiment, the participant tried to evaluate distance by keeping track of paces.
  - The participant thought that they walked faster at the end.
  - The participant noted that the grid used to verify the calibration between the room and the HMD was a particularly uncomfortable color.
  - The participant had been studying on a computer all day before this experiment.
  - The participant noted that the headset was uncomfortably warm.

- Subject 27
  - The participant said that the Magic Leap headset was uncomfortable.
  - The participant was operating on 3 hours sleep.
  - The participant did not find anything distracting.

- Subject 28
  - The participant heard snapping noises from the experimenter's clipboard.
  - The participant felt they were overthinking the experiment towards the end.
  - The participant was using a patch of odd-colored tiles within the room as a location tool.
  - The participant noticed that targets were at the center of the room (on the left/right plane) and that there were three main targets.
  - The participant noticed the room's odd AC and the location of the light sources within the room, but had difficulty using those to improve spatial understanding or self-locate.
  - The participant noticed a difference between left and right; they felt more oriented in the walk to the right.

- Subject 29
  - The participant had difficulty wearing the Leap; the device would slide down their hair.
  - Fiducial calibration was off by a few inches at start, based on the participant's understanding of the room geometry.
  - The participant evaluated their position, the wood chip, and the target and made a triangle from those in their mind.
  - The participant did not find anything distracting, other than the slipping HMD.

- Subject 30
  - The participant noted that fiducial calibration was a bit off before the experiment, based on the participant's understanding of the room geometry.

  - The participant found the headset a little uncomfortable after some time. The participant's ears, in particular, hurt a bit.
  - The participant had to move their head a little to see the target in the virtual target condition.
  - The participant did not find anything distracting.
  - Participant visualized wood chip, target position, and their own position while walking.

- Subject 31
  - The participant adopted a strategy of using angles by pointing with their foot.
  - The participant walked with a particularly fast pace; they also stopped quickly.
  - Particularly early on, the participant moved their head a lot when looking at the target.
  - The participant had to restart the program a few times.
  - The participant did not find anything distracting.

- Subject 32
  - The participant thought the experiment was similar to the walking outside experiment (Experiment 1).
  - The participant thought about the task in terms of angles; they pre-calculated the angle.
  - The participant tripped once, but had no other distractions.

- Subject 33
  - The participant thought the experiment was neat.
  - The participant felt more uncertain as they walked toward the virtual target.
  - The participant said they stumbled a bit early on in the experiment.
  - The participant mapped out the angle in advance.
  - The participant felt better walking to farther distances.

- Subject 34
  - For the first couple of data points, the participant did not fully turn around while the experimenters were taking data and modifying the object position.
  - The participant did not find anything distracting.
  - The participant thought that walking around with their eyes closed was interesting and different.
  - The participant tried to create a mental triangle from the object, wood chip, and their own position.

    - The participant felt like they overrated their shape visualization ability in the general questionnaire.

- Subject 35
    - The participant wasn't bothered by wearing HMD; they said it felt like wearing headphones.
    - The participant noticed targets were on the same line but at different depths.
    - The participant reported that the wood chip position seemed different between the first and second halves of the experiment.
    - The participant imagined the angle they would need to turn if standing at the wood block's position and then compensated slightly to account for stopping a little short of that position.
    - The participant used light as a cue. They noticed when they had passed the shadow of the wall by the light coming through their closed eyes being a bit brighter. Eventually, the participant started noticing the step number that this happened on.
    - The participant felt like they couldn't keep track of their position as they were being led back to the starting location; they tended to be a bit disoriented when opening their eyes.

- Subject 36
    - The participant felt distracted and somewhat sleep-deprived.
    - The participant noticed that the virtual target had some jitter (1-2 cm), both visually shaking and perceptually appearing at different distances or over/in the floor.
    - The participant thought that their spatial awareness was pretty good.

- Subject 37
    - Seeing virtual objects felt weird to the participant; the participant reported that they seemed to float on top of the floor.
    - The participant did not find anything distracting, though they mentioned that wearing the headset for a while was a little uncomfortable.
    - The participant mentally drew a line from their position to the woodchip, stopping just short. They then used this line to calculate the angle to the object.

- Subject 38
    - The participant did not find anything distracting.
    - The participant traced a line from the target to the wood chip. They considered the turn angle and practiced turning before walking toward the wood chip.

- Subject 39
  - The Magic Leap system couldn't detect the participant's eyes.
  - The participant forgot their contacts.
  - The participant did not find anything distracting.
  - The participant evaluated the angle between the wood chip and the target, but then compensated somewhat, recognizing that they were stopping before reaching the wood chip.
- Subject 40
  - The participant did not find anything distracting.
  - The participant used the angles of the visible objects as a method to calculate the amount of turning they would have to do.

Experiment 4

- Subject 41
  - The participant noted that the object followed a pattern up and down a line.
  - The participant reported that it was harder to tell depth when the wall shutter was up.
  - The participant heard a few loud clunks (the clipboard); they did not report any other distractions.
  - The participant felt like they memorized certain distances and remembered them between trials.
- Subject 42
  - Once the screen was on, the participant had to compensate; they reported that it ”changed everything.”
  - The participant did not find anything distracting.
  - The participant considered where a right angle turn would take them; they calculated how much more than a right angle they would need to turn.
- Subject 43
  - The participant noticed split images when walking from both sides; this remained distracting for the first two conditions, but cleared up by the third condition (opaque wall).
  - The participant sometimes closed one eye to see more clearly; they felt like the view from their right eye might be better.

- Felt less confident after switching sides. The participant felt more accurate during the first half of the experiment.
- When asked about distractions, the participant responded that they felt like they walked a little like they were drunk. (The experimenter did not observe any particularly poor balance for this participant.)
- The participant looked at the wood chip and target to evaluate distance, but then ”felt” what the distance was when they could not quite remember.
- Participant split the targets into near, medium, and far distances.
- The Magic Leap could not be calibrated for this person.

• Subject 44

- When walking towards the wood chip, the participant would slow down and stop a bit before the experimenter said.
- The participant thought the experiment was interesting.
- The participant felt like the presence of the opaque wall reduced accuracy.
- The participant felt like the presence of the virtual window neither added nor took anything away, perception-wise.
- The participant put a good bit of effort into placing the virtual object in their mind before walking to it.
- The participant did not find anything distracting, but they mentioned that the AR display appeared in the top half of their vision.
- The participant swayed a bit before walking.
- The participant reported that they had no particular strategy; they turned toward what felt ”right.”
- Participant noticed the object appeared a bit shaky sometimes.

• Subject 45

- The participant noticed a rainbow hue from the fluorescent lights. (The participant could tell they were from the fluorescent lights because they disappeared when the participant shaded their eyes.)
- The participant reported that the virtual window shifted up over time; they found that this was due to the Leap headset slowly sliding down on their head.
- The participant reported that occasionally things shifted in and out of focus.
- The participant reported that the virtual window was a little off; it was a bit in front of the real window and a little bit bigger.
- The participant had an idea of how big the target was; they thought that this may have improved their effectiveness.

  - The participant noticed some apparent texture on the ground through the virtual window. They reported that it seemed liked some sort of triangle pattern.
  - The participant thought that they were in a different place in the room sometimes when they opened their eyes.
  - The participant was used to navigating in the dark and felt comfortable walking with their eyes closed.
  - Early on, the participant considered the line/angle from the woodchip to the target; later on, the participant thought about the distance they needed to walk to be at a right angle to the target.

- Subject 46

  - The participant said that they lost their footing a bit.
  - The participant felt like they knew where the target was at start, but felt confused when they needed to turn.
  - The participant visualized object location continuously as they walked.

- Subject 47

  - The participant's eyes got a bit tired.
  - The bridge of the participant's nose felt a bit rough through the experiment.
  - The room seemed smaller when the participant closed their eyes.
  - The participant measured the position of the object relative to self and plotted the path to turn. Then they made a big/medium/small turn.
  - Window was weird-kind of brought on an expectation of distortion, like a glass window.
  - The participant did not find anything distracting.
  - The participant reported that their field of view was small; they had to lean back to see both target and wood chip at the same time.
  - The participant mentioned that we may want to filter out blue light, which can cause eye strain and damage.

- Subject 48

  - The participant felt like they underestimated the distance to the target; they thought that they regularly understood the wall as closer than it really was.
  - The participant used angles between each of the relevant objects to calculate the amount of turning needed.
  - The participant perceived a floor surface through the virtual window.
  - The participant did not find anything distracting.

  - The participant thought about the noise from the opening and closing of the room door.
  - The participant recommended that we consider changing the color of the target object; they said that lots of green can be distracting.
  - The participant noted that color could potentially be used to trigger better memory effects.

- Subject 49

  - When they were closer, the participant turned almost 180 degrees; when farther, they took more steps.
  - The participant felt they swayed on feet a bit; they never felt like they were gonna fall over, however.
  - The participant tried to do 7 paces for each trial.

- Subject 50

  - The participant did not find anything distracting.
  - The participant felt like they were in a video game; the participant ”felt” where objects were.

- Subject 51

  - The participant had some visual difficulty with most VR; this included difficulty with stereo fusion and prescription glasses that were not worn.
  - The participant thought that the virtual window was distracting; they felt it did not help and maybe misrepresented the room.

- Subject 52

  - The participant reported that targets seemed closer when the physical screen was up.
  - The participant couldn't discern an accuracy/comfort difference between the opaque wall condition and the virtual window condition.
  - The participant was a little distracted by the sound of the vent; they resisted the urge to use it to triangulate.
  - The participant started off considering the amount they would need to turn at the wood chip, but eventually started imagining the turn amount at a distance in front of the wood chip.
  - The participant practiced grabbing towards the target during initial viewings of the target.

- Subject 53

- The participant found that some virtual objects shifted slightly while the participant focused on them.
- The participant mentioned having limited working memory; they felt like they forgot the target location sometimes.
- The participant paid attention to the relative position of the wood chip and target. Before the wall cover was used, the participant's judgments incorporated the target's room position.
- The participant noted the opacity of the virtual window; they mentioned that they wouldn't expect to see through something of that color in real life.

• Subject 54

- The participant felt good, perceptually, about the open window and closed window conditions, but felt less confident about the virtual window condition.
- The participant perceived a floor or wall shade/structure through the virtual window.
- The participant had no specific strategy but mapped out the angle ahead of time.

• Subject 55

- The participant had to work a little harder to visualize room. This was especially true when the physical screen was up.
- The object appeared to change in size based on distance; this effect was more pronounced when the physical screen was up.
- When asked about distractions, the participant reported that the headset slid down their head a little early on but that, otherwise, there were no distractions.
- The participant created a mental triangle all the way to the woodchip in order to estimate the needed turning angle; they mentioned that may have effected the result.
- The participant had difficulty understanding the size of the room with their eyes closed; they felt uncertain.
- The participant thought about personality; they wondered if that might have something to do with their claustrophobic feelings when they navigated the room with eyes closed.

• Subject 56

- The participant turned toward the target in order to view it; they turned back toward the woodchip before walking.
- The participant used a triangulation approach incorporating a tape mark and the fiducial that was positioned in the center of the room. They used that in conjunction with the woodchip to evaluate the necessary turning angle.
- The participant felt the target was close to the wall in the far distance.

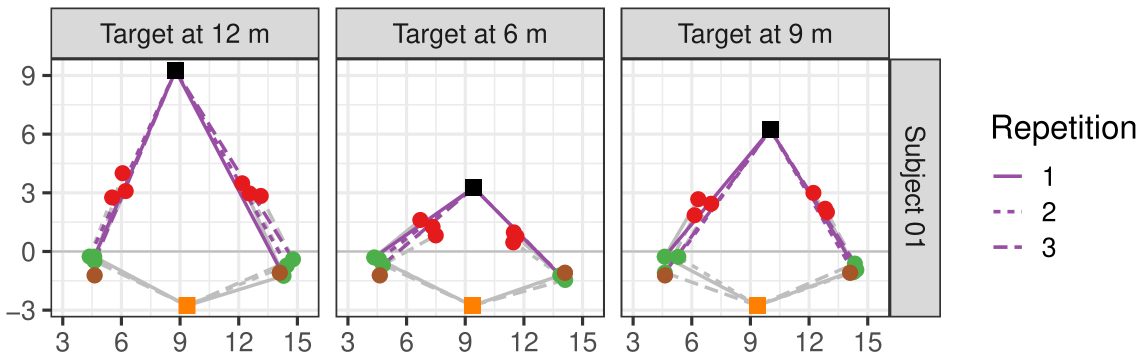
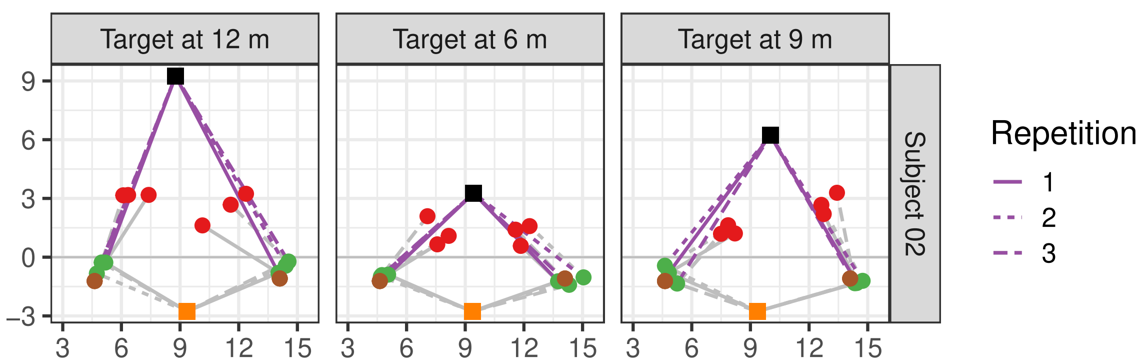
- The participant did not find anything distracting.
- The participant felt like they stopped at a specific tape mark before turning; this was mostly accurate for this participant.

- Subject 57
  - During the experiment, the back of the Magic Leap slipped and rotated down a bit on the participant's head; this caused some framing issues. (The front of the Leap rotated up, and the viewing pane started to drift toward the top of the participants' field of view.)
  - When viewing the target, the participant felt that accuracy was more about their head rotation than any other variable.
  - The participant noted that having an HMD with a strap across the crown might help prevent slippage.
  - The participant navigated by light and sound as well as their initial vision.
  - The participant counted steps.
  - The participant reported noticing 4 different, repeated distances.
- Subject 58
  - The participant mentioned that they had a little bit of a headache and some eyestrain after the experiment.
  - If the target was in the far position, the participant turned almost 90 degrees; if it was near, they turned less.
  - When the physical screen was up, it was harder to evaluate the distance.
- Subject 59
  - The participant found the virtual window (which they called the ”blue shield”) interesting.
  - The participant did not find anything distracting.
  - The participant sensed where the room lights were and used that for feedback on their position; the participant evaluated their turn angle based on the angle between the wood chip and the target.
- Subject 60
  - The participant reported that the Leap was a bit uncomfortable after about an hour.
  - The participant reported that virtual objects felt slightly off from the real world; the farther away the target, the harder it was to appropriately estimate depth.
  - The participant did not find anything distracting.
  - The participant drew a mental line between their perceived self-location, the wood chip, and the target; they used that to calculate the turning angle.

APPENDIX C

PARTICIPANT WALKED PATHS

Table C.1: Experiment 1 Walked Paths

Experiment 1 Walked Paths



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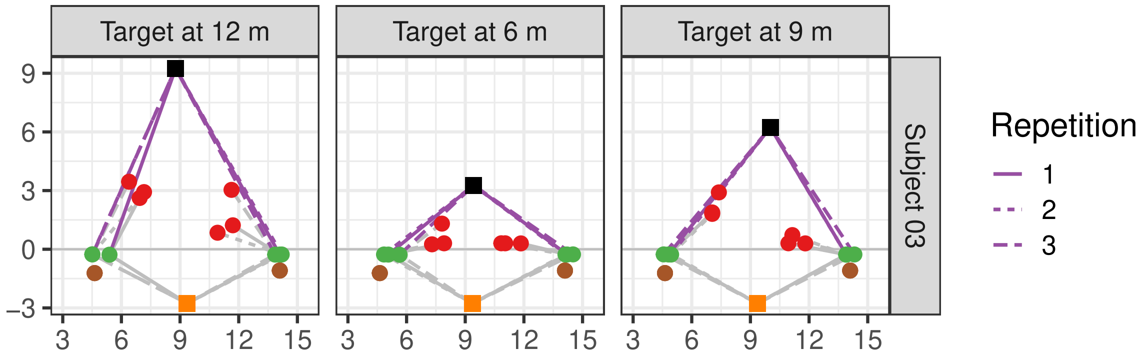
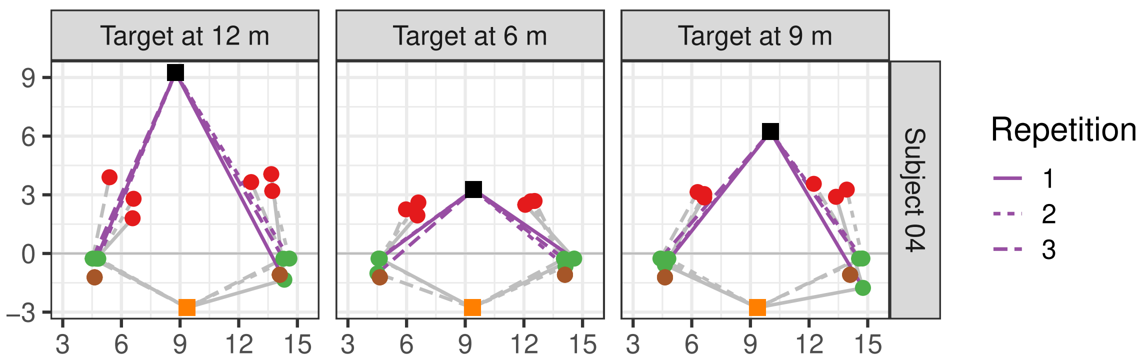

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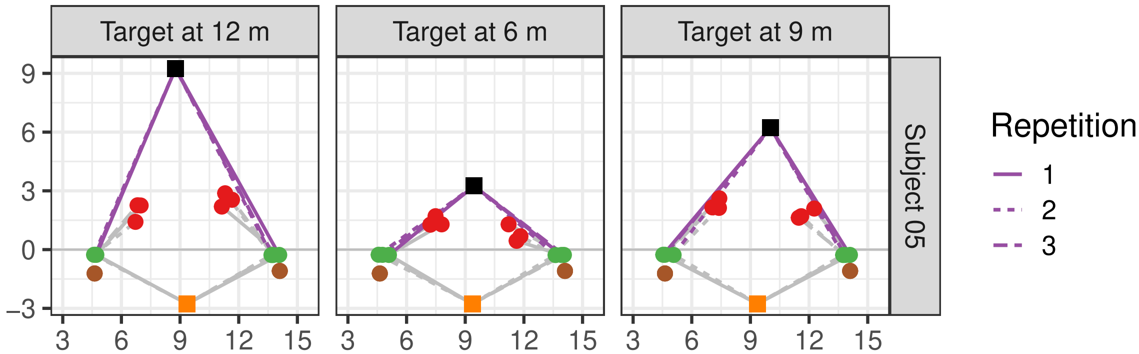
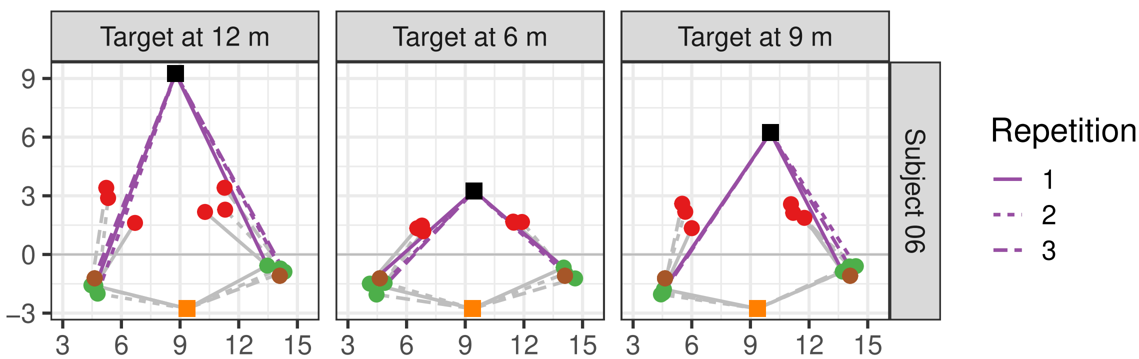

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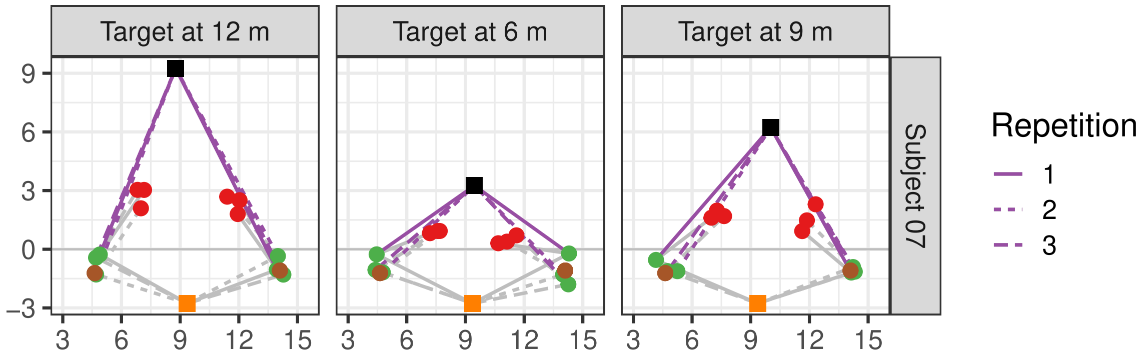
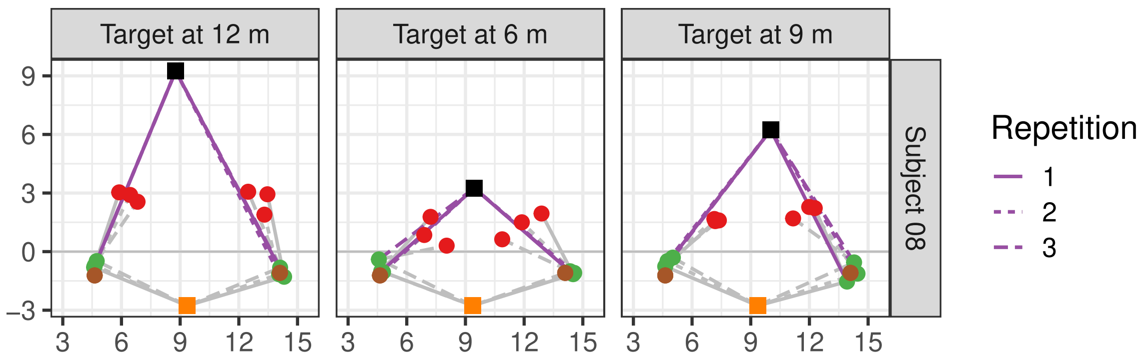

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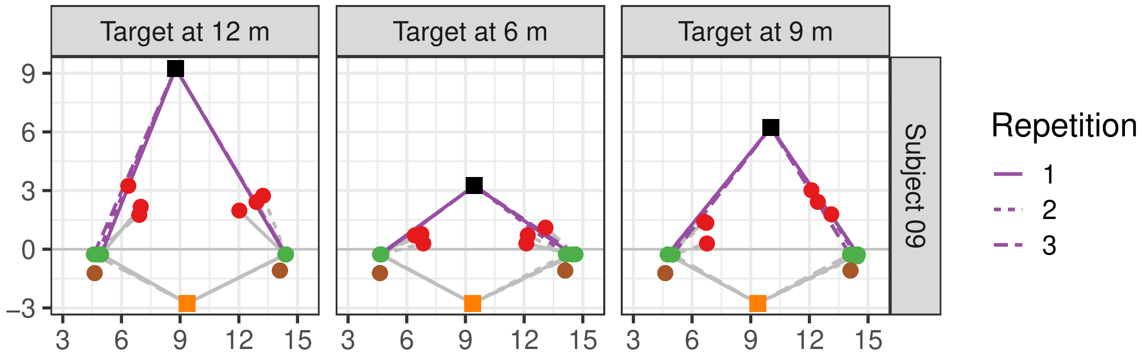
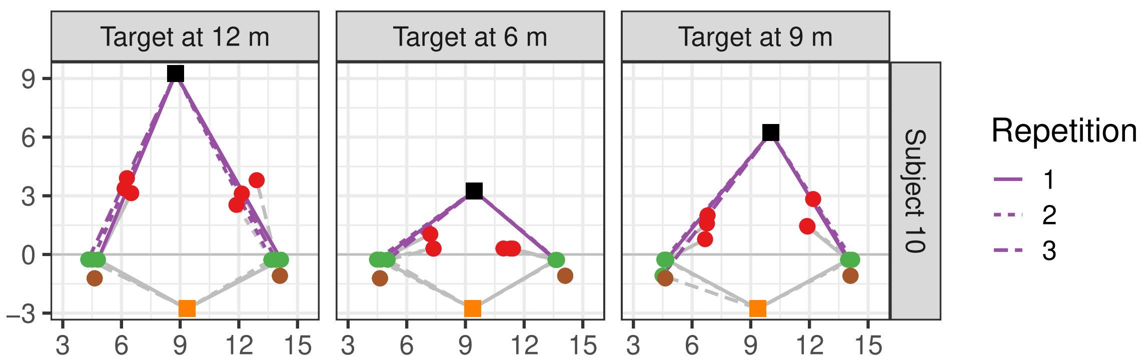
Experiment 1 Walked Paths





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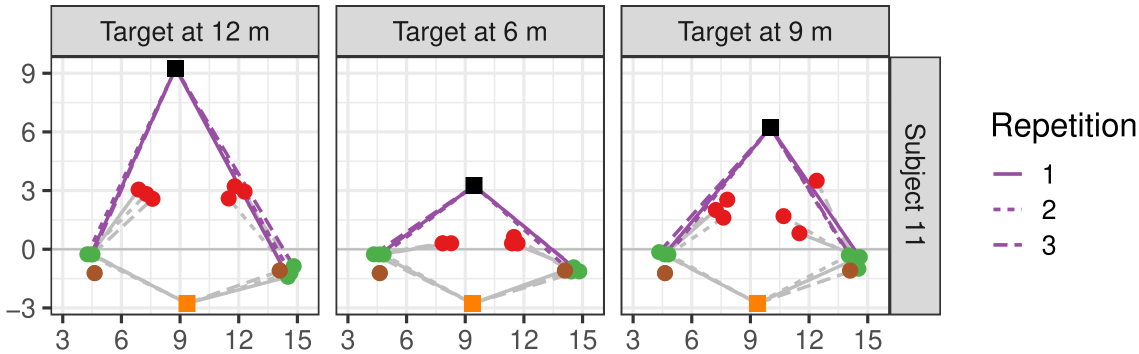
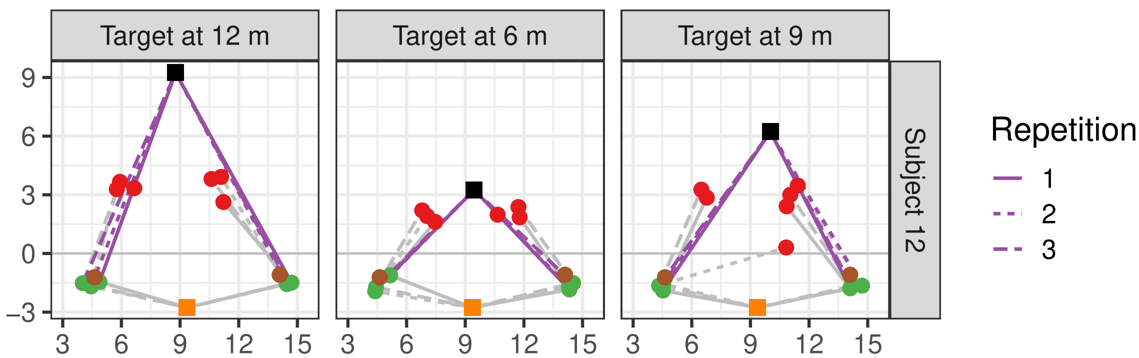

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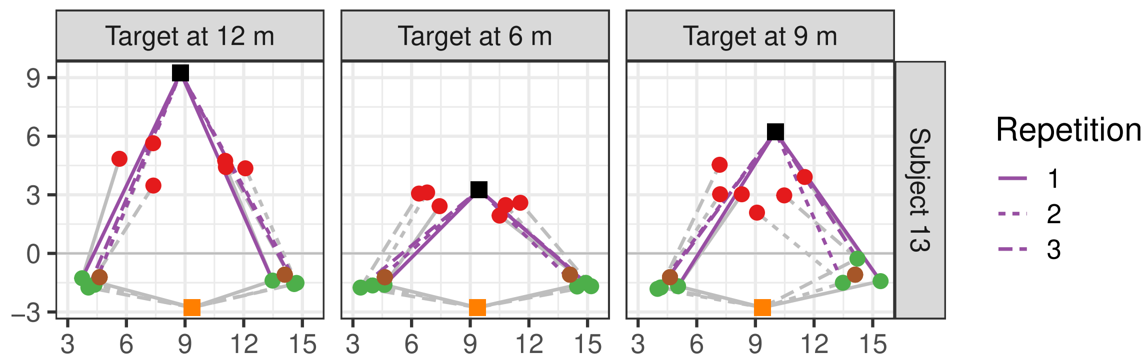
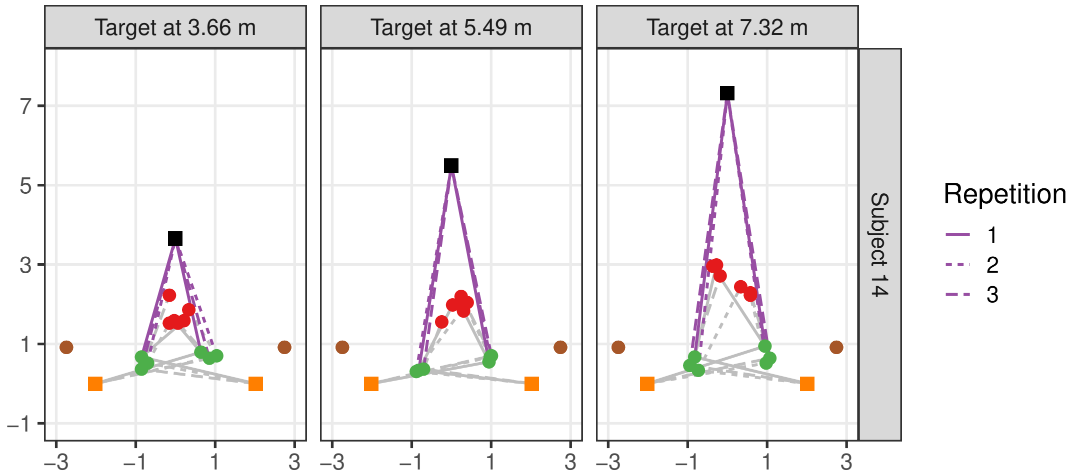
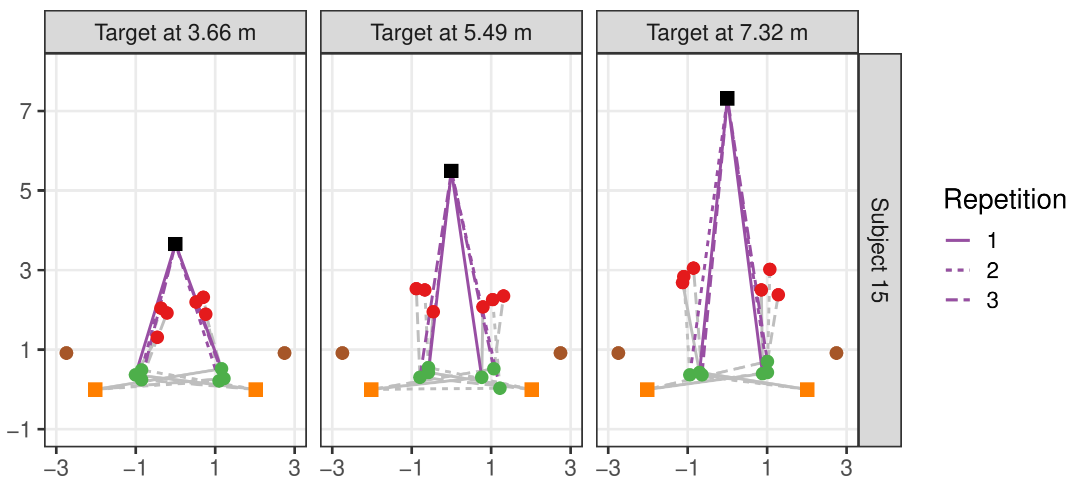


Table C.1: The walked paths of Experiment 1 $(N = 13)$. The orange points represent starting location; green, turn points; brown, experimenter location; red, stop points; the purple lines, correct paths to the target; the grey lines, actual walked paths; and the black point, target location. Target distance from the starting point is labelled at the top of the graph.

Table C.2: Experiment 2 Walked Paths

Experiment 2 Walked Paths





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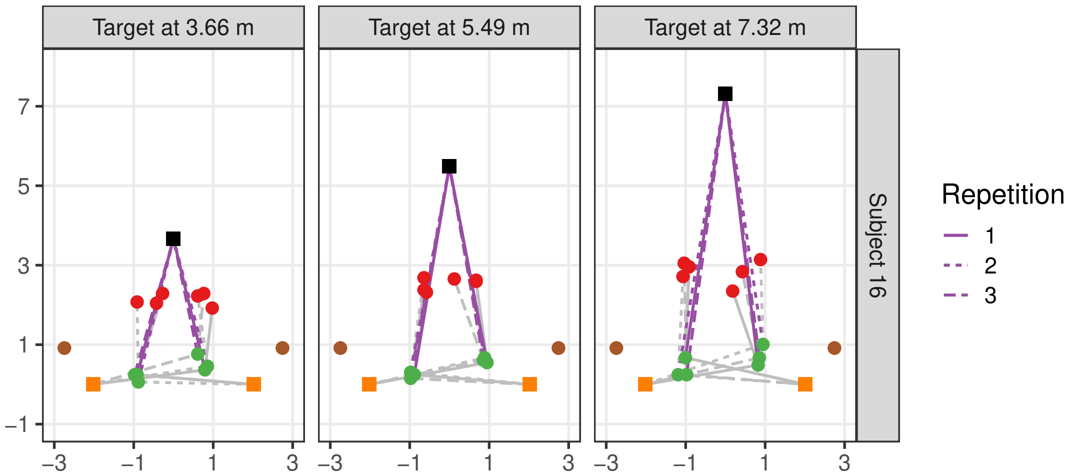
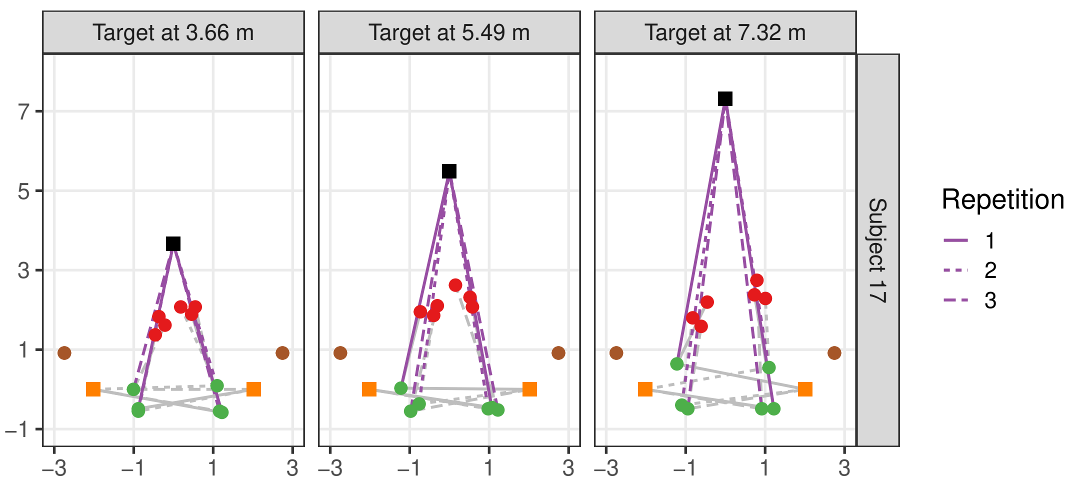

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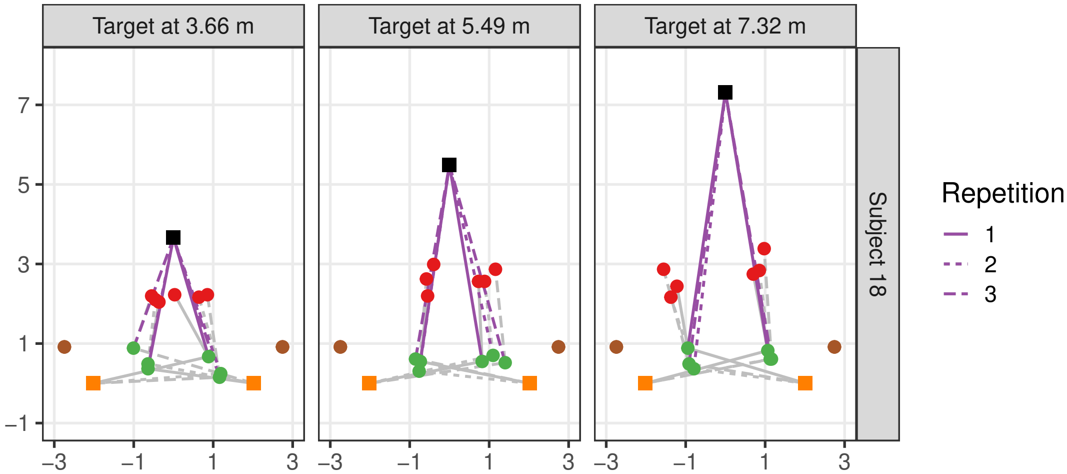
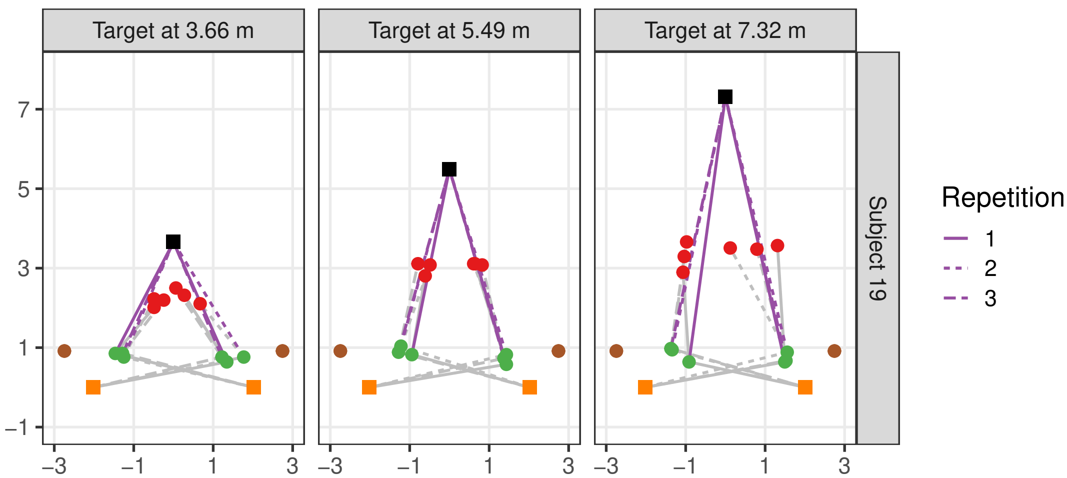

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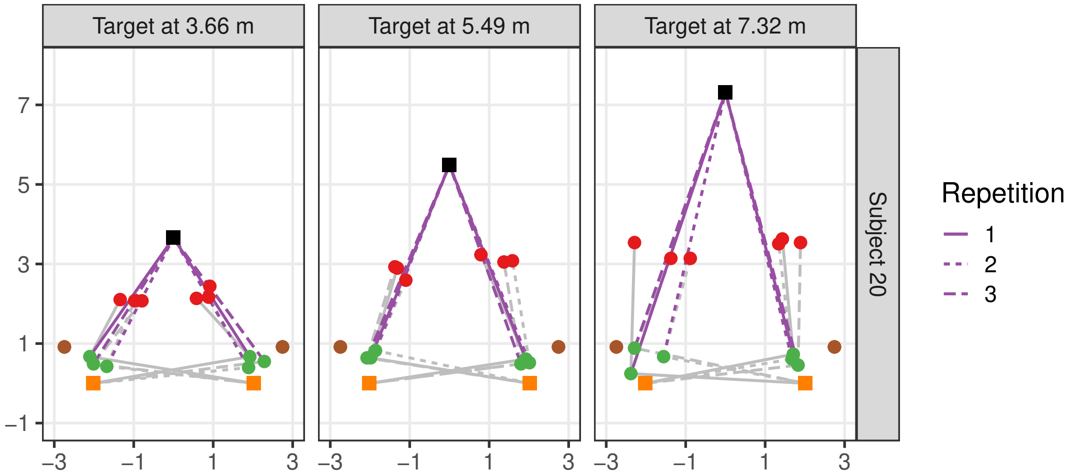

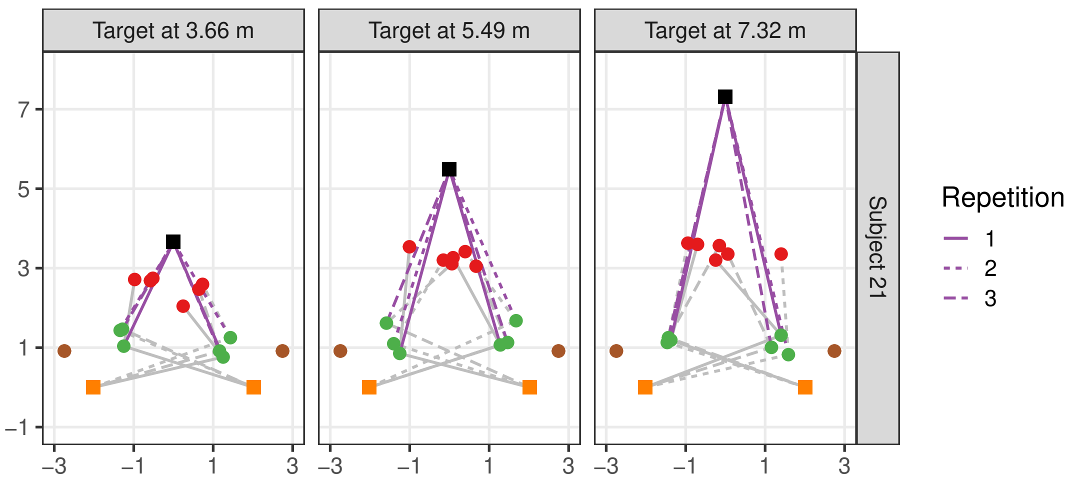

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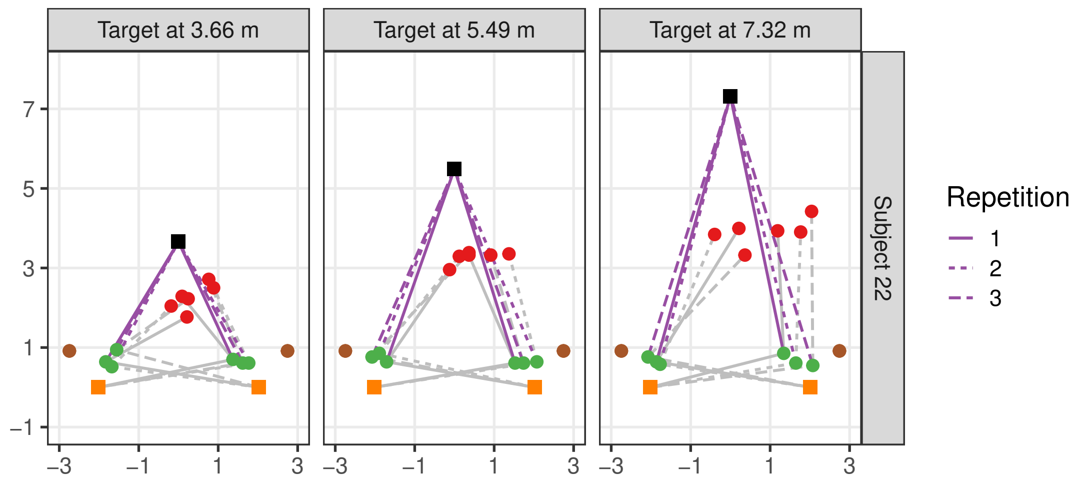
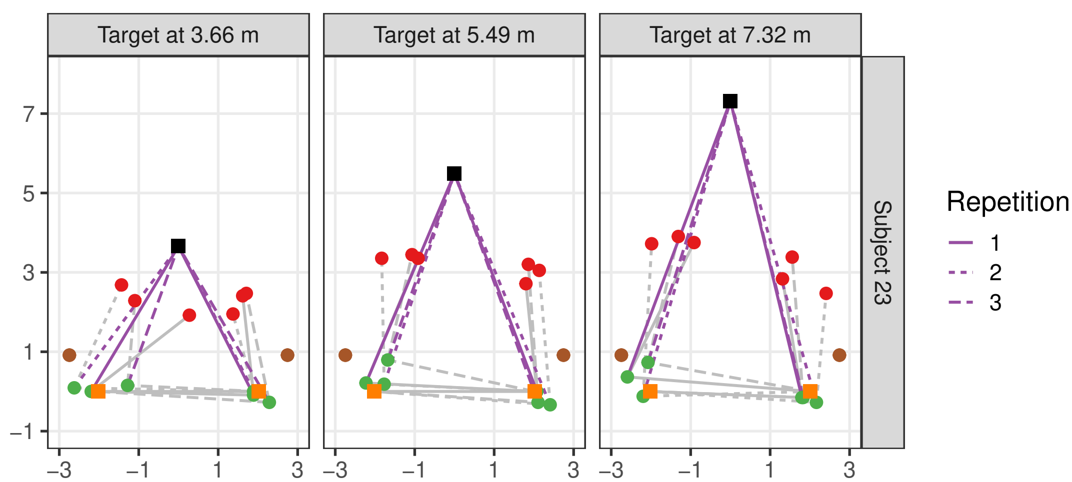

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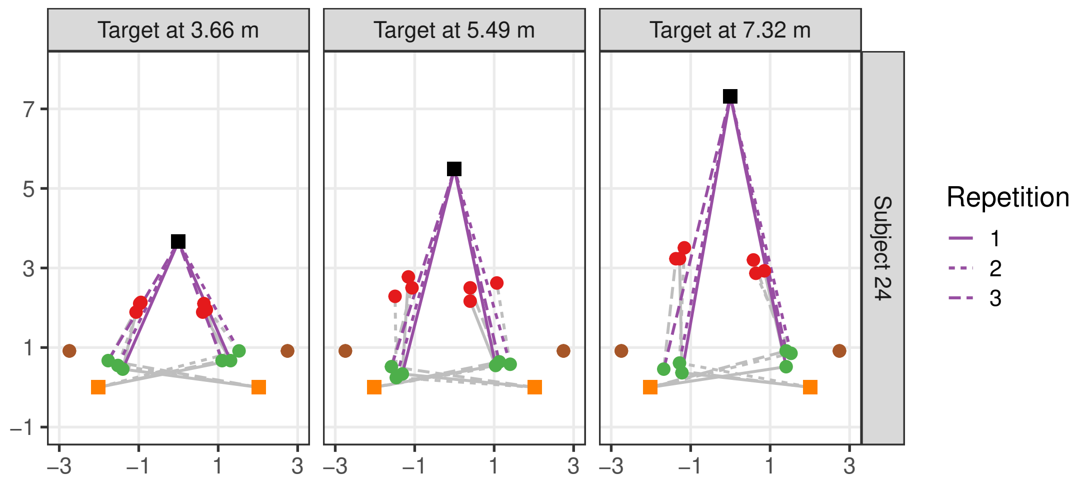
Experiment 2 Walked Paths



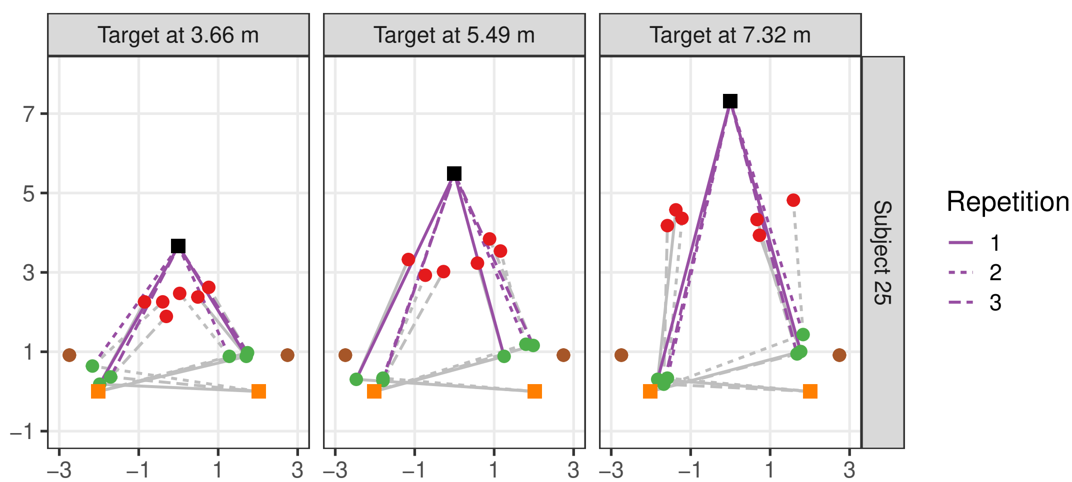
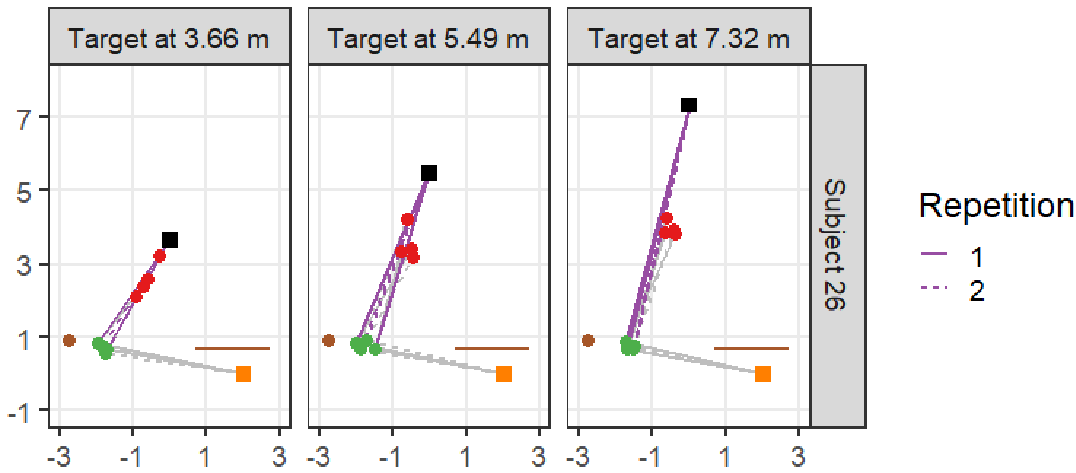
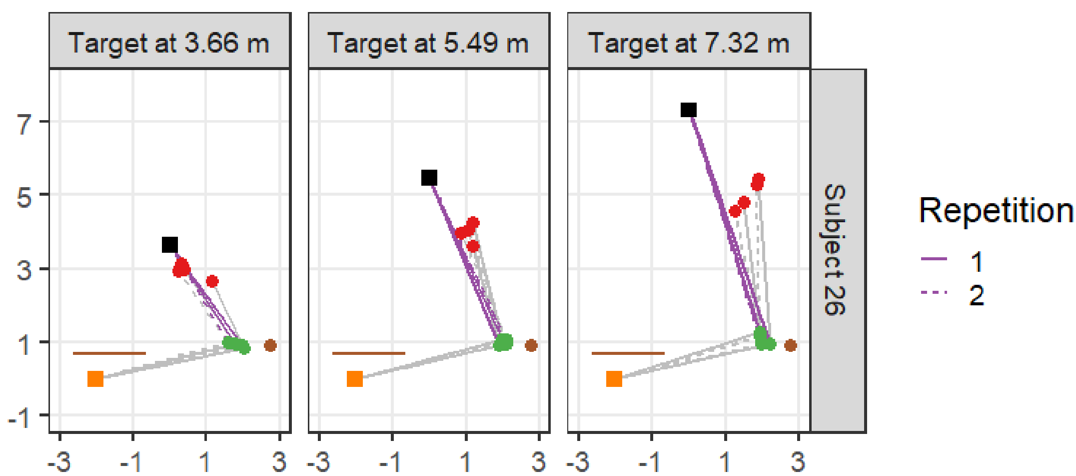


Table C.2: The walked paths of Experiment 2 ($N = 12$). The orange points represent starting location; green, turn points; brown, experimenter or wood chip location; red, stop points; the purple lines, correct paths to the target; the grey lines, actual walked paths; and the black point, target location. Target distance from the origin is labelled at the top of the graph.



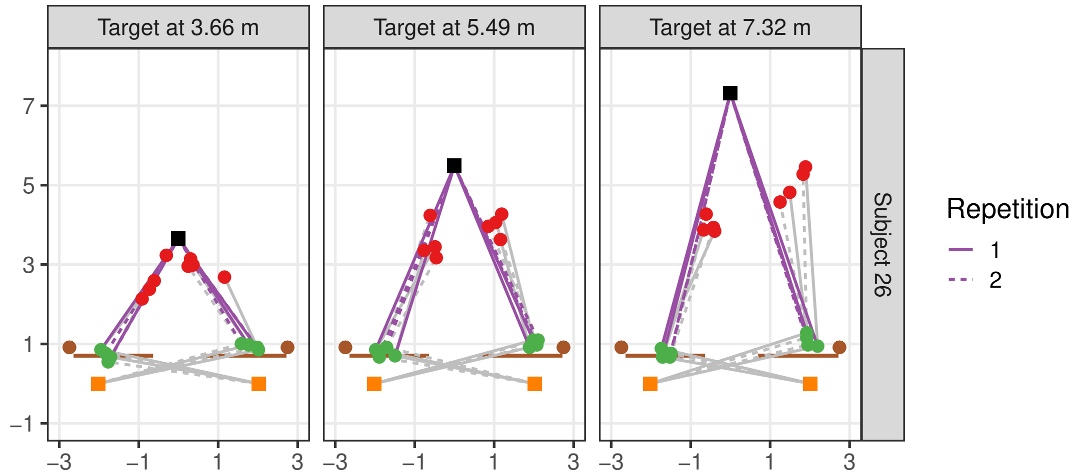
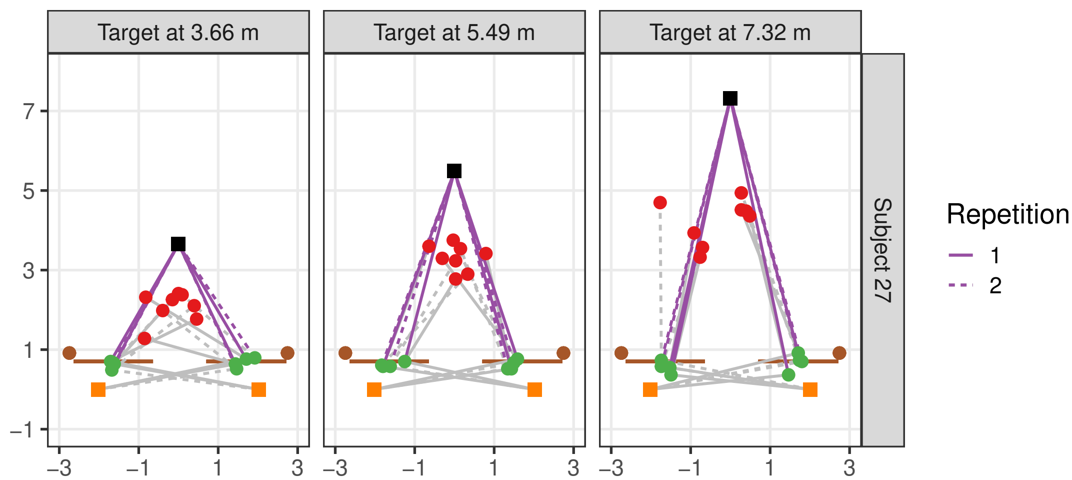
(a) Left Walk



(b) Right Walk

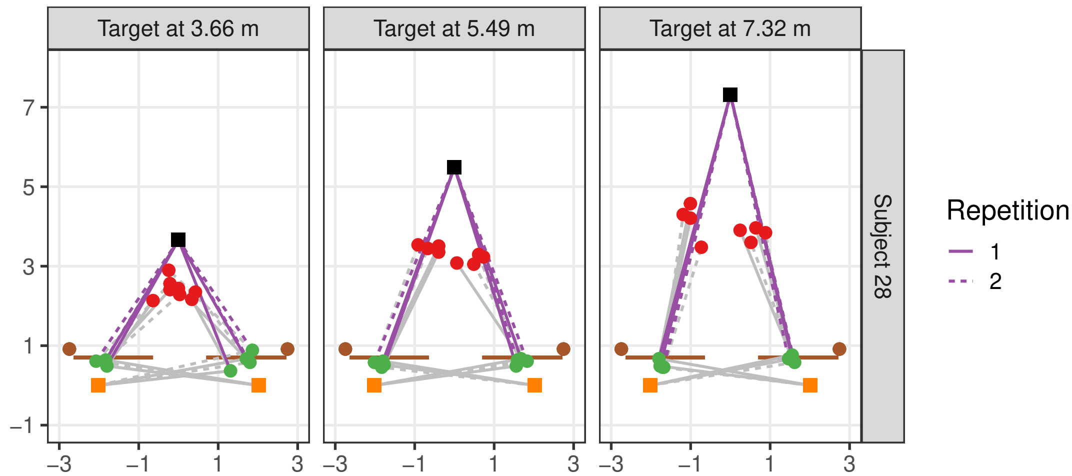
Figure C.1: The actual wall position in Experiments 3 and 4, during left and right walks $(N = 1)$. For simplicity, both walks are combined in Tables C.3 and C.4.

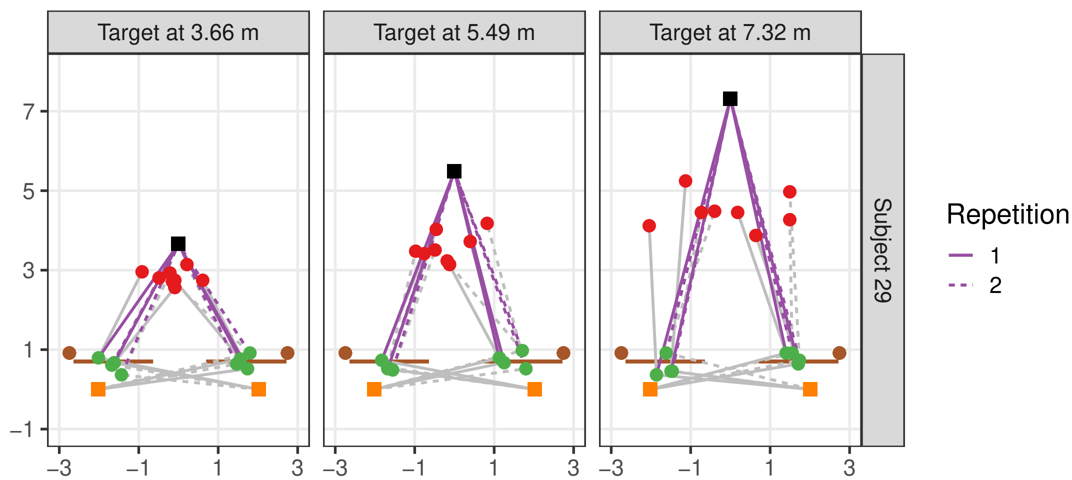
Table C.3: Experiment 3 Walked Paths

Experiment 3 Walked Paths



Continuation of Table C.3

Experiment 3 Walked Paths





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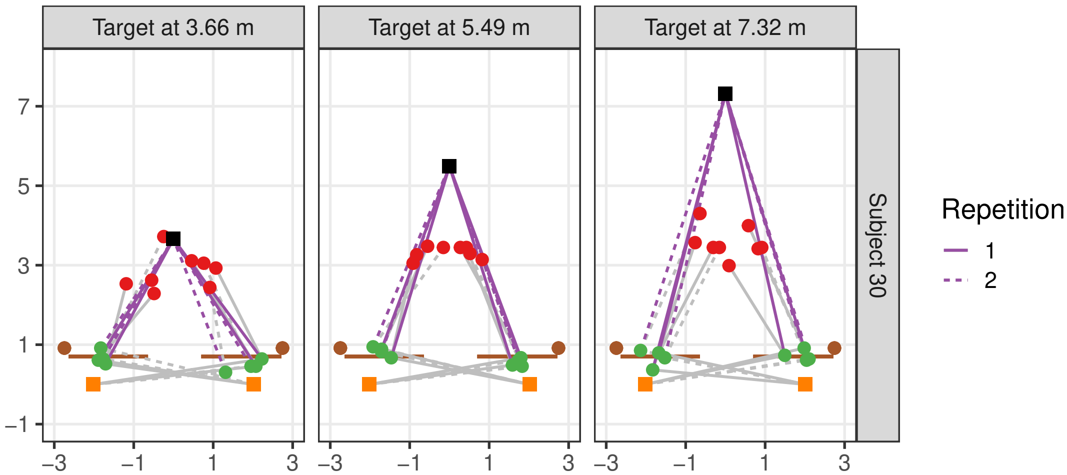
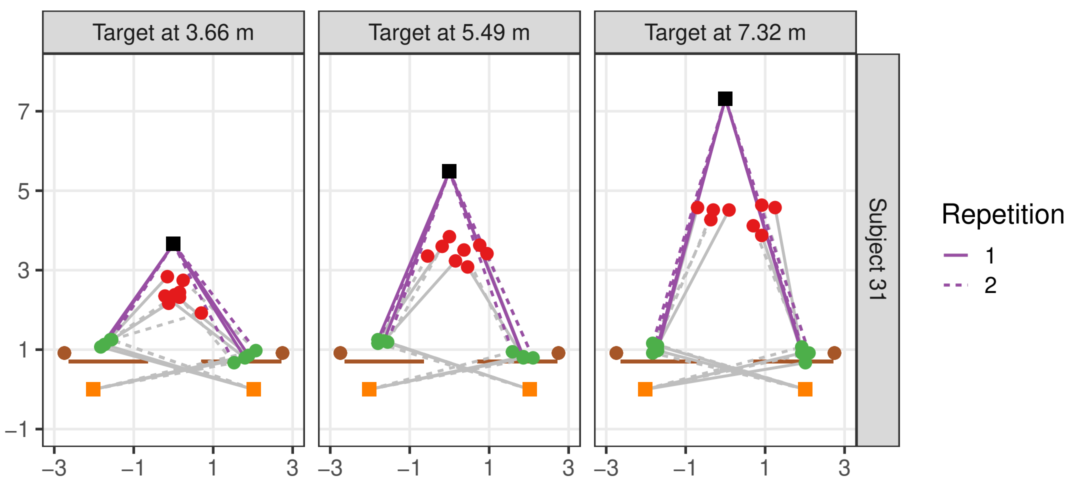

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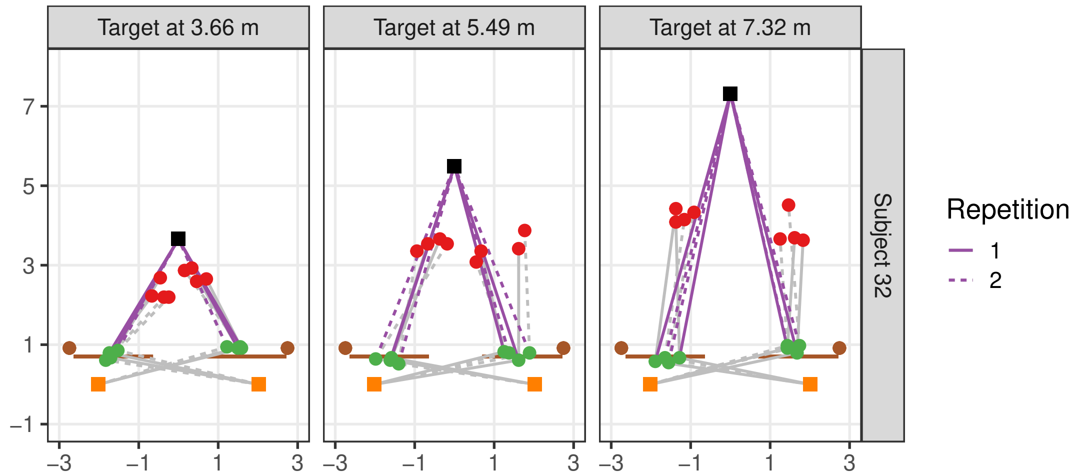
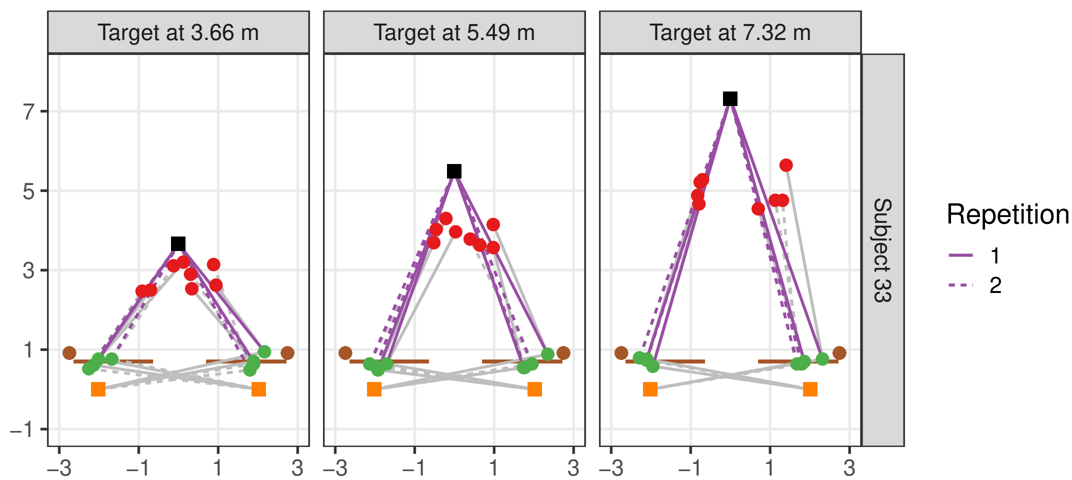
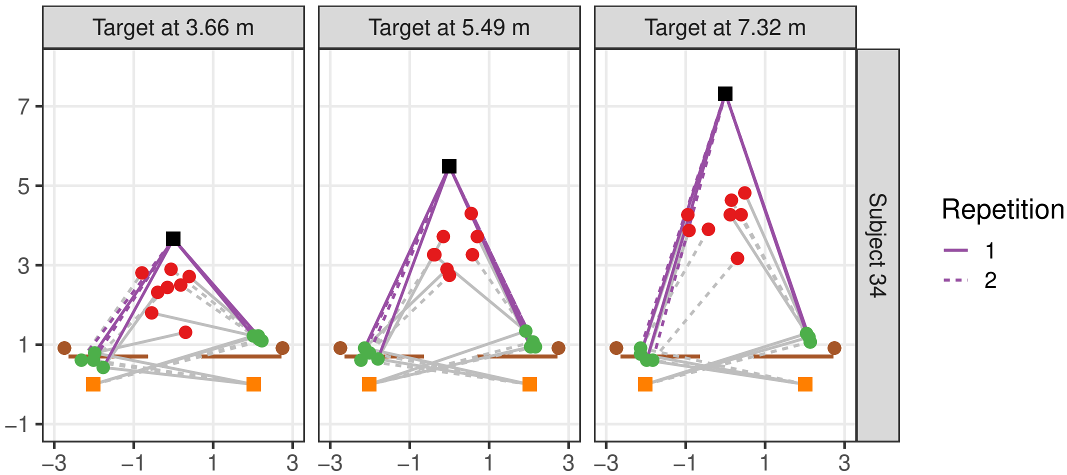
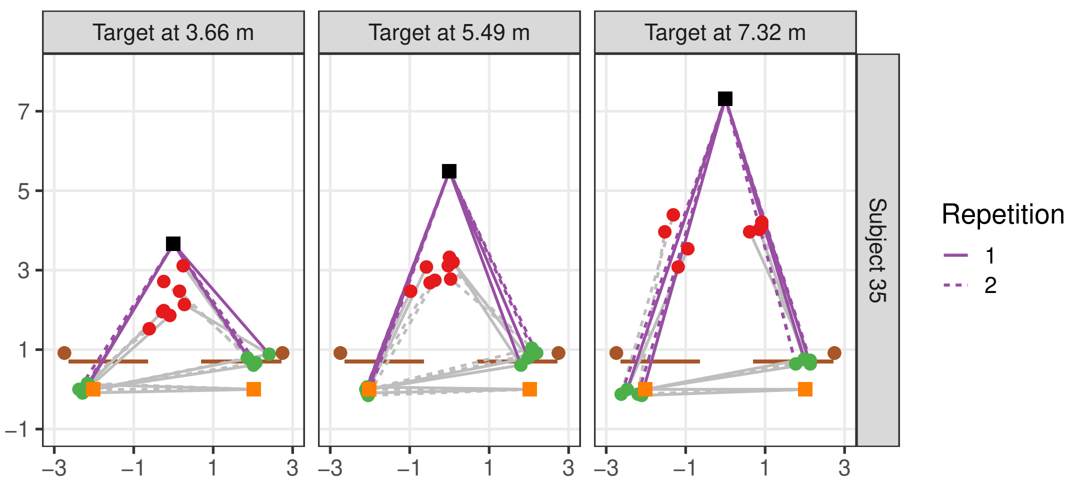




Continuation of Table C.3

Experiment 3 Walked Paths





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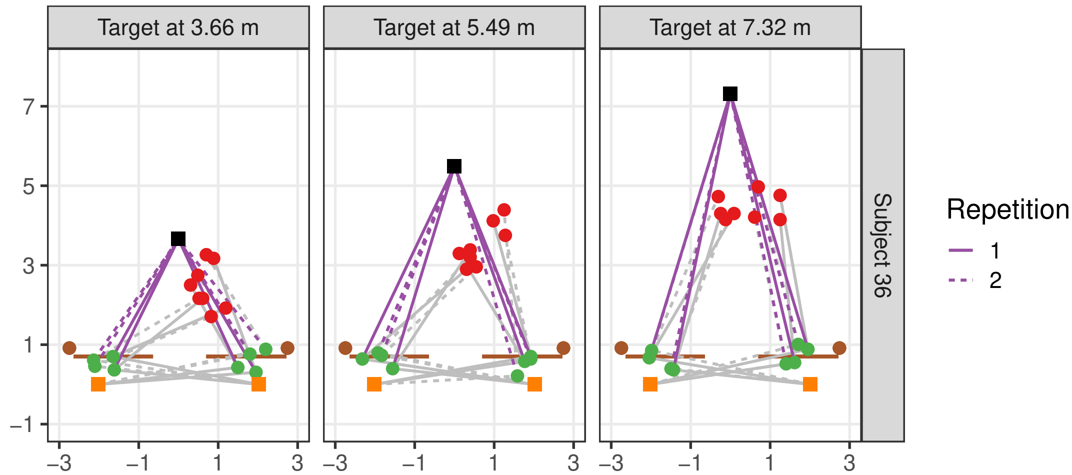
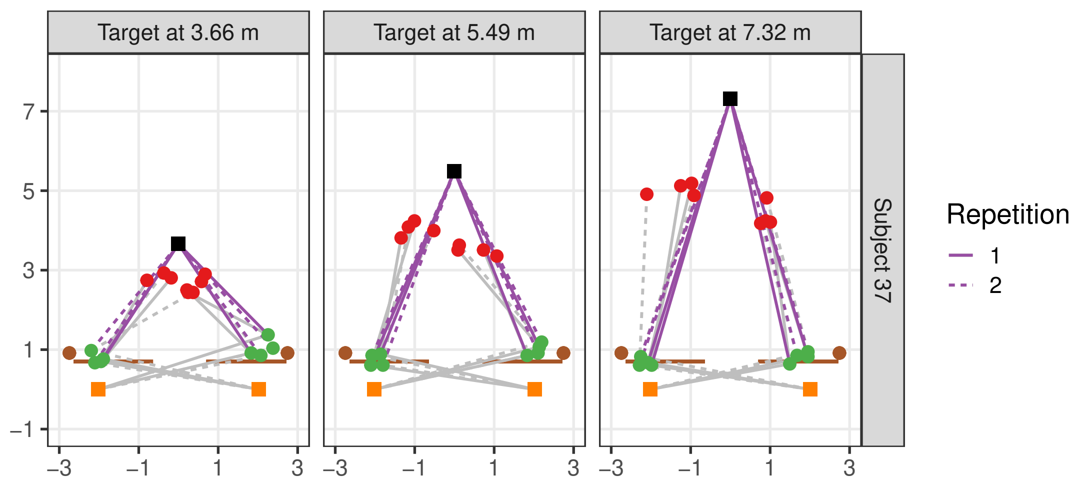

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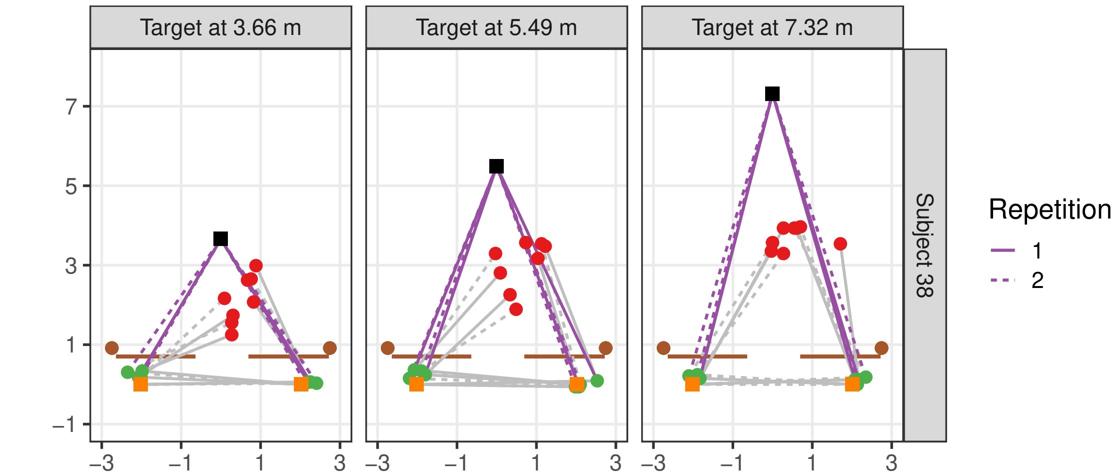
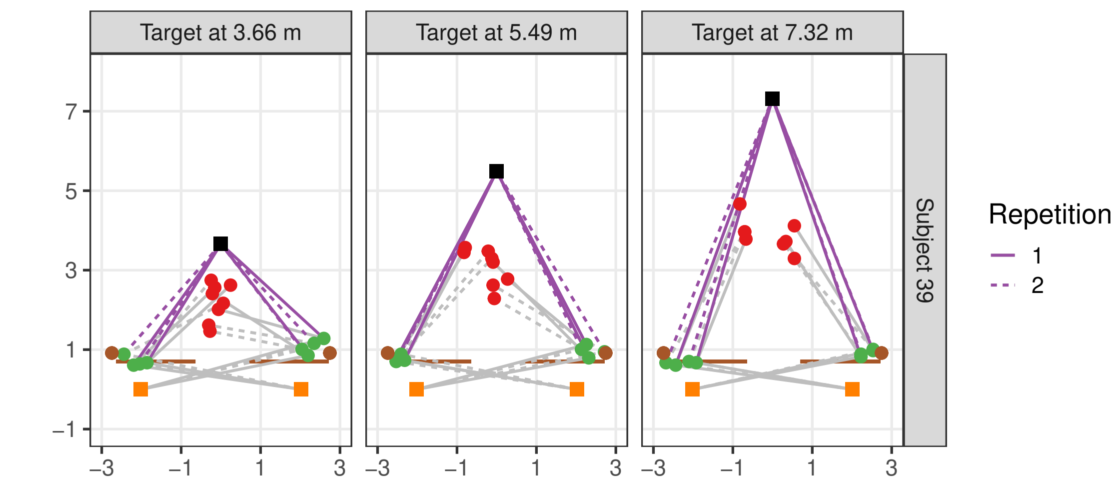
Experiment 3 Walked Paths





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Experiment 3 Walked Paths

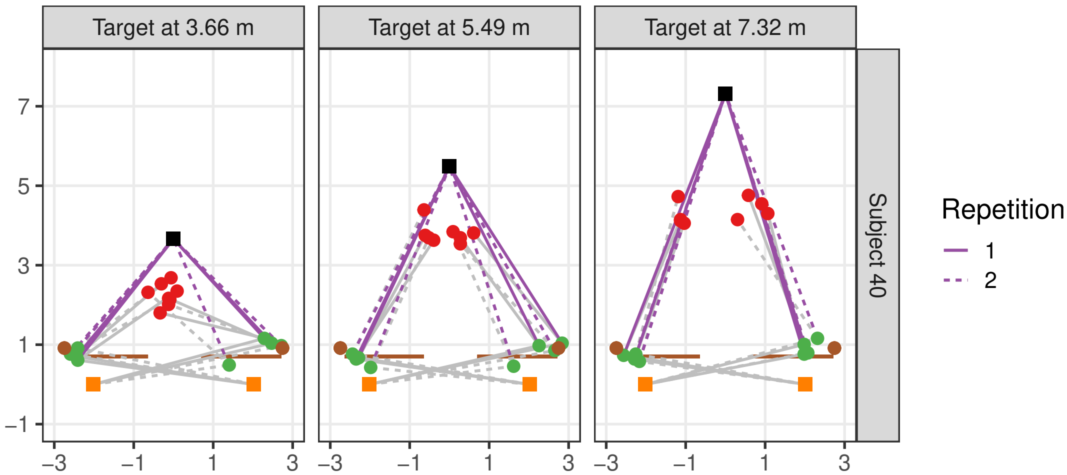
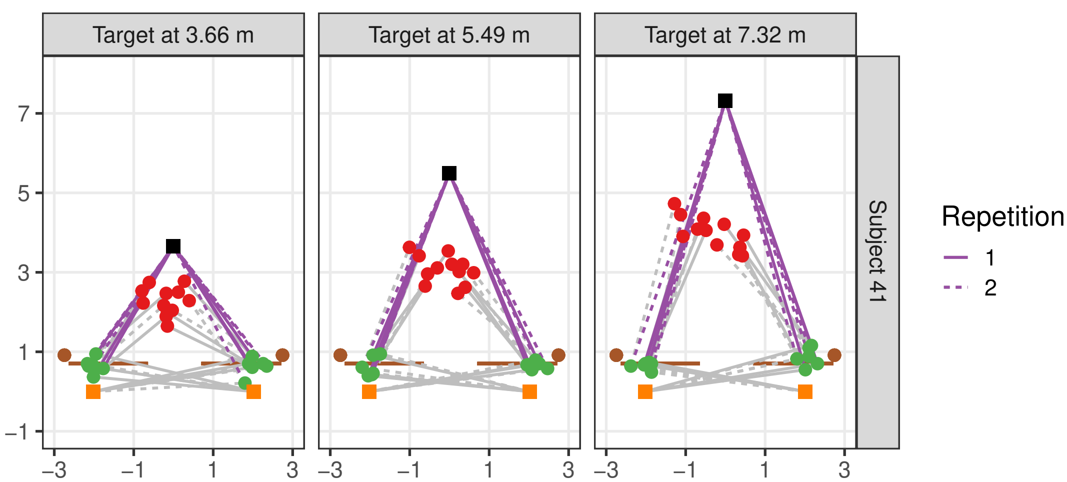


Table C.3: The walked paths of Experiment 3 ($N = 15$). The orange points represent starting location; green, turn points; brown, wood chip location; red, stop points; the purple lines, correct paths to the target; the grey lines, actual walked paths; the brown lines, wall location (Figure C.1); and the black point, target location. Target distance from the origin is labelled at the top of the graph.

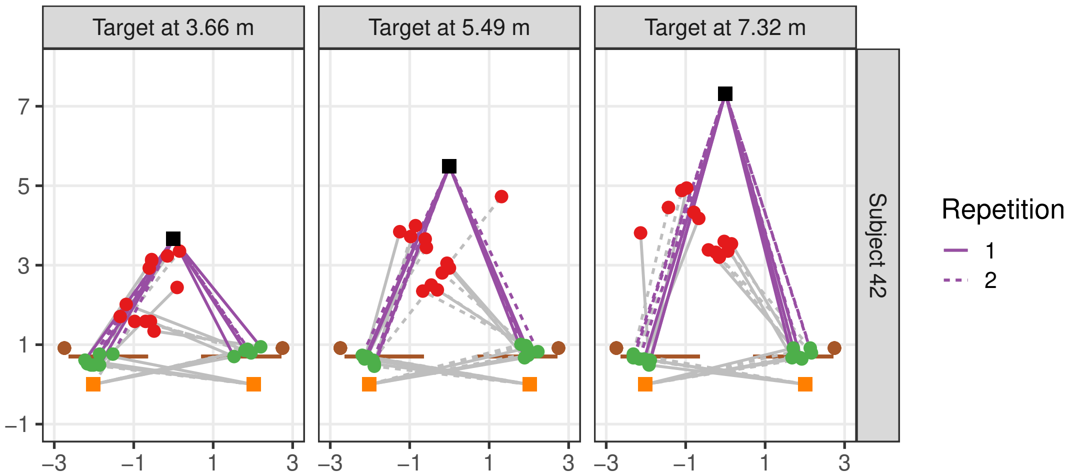
Table C.4: Experiment 4 Walked Paths

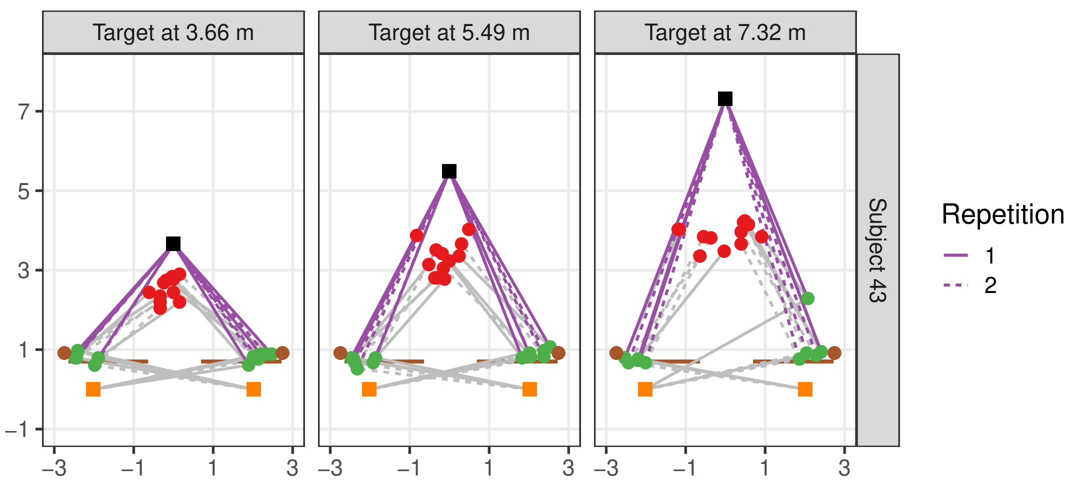
Experiment 4 Walked Paths



Continuation of Table C.4

Experiment 4 Walked Paths





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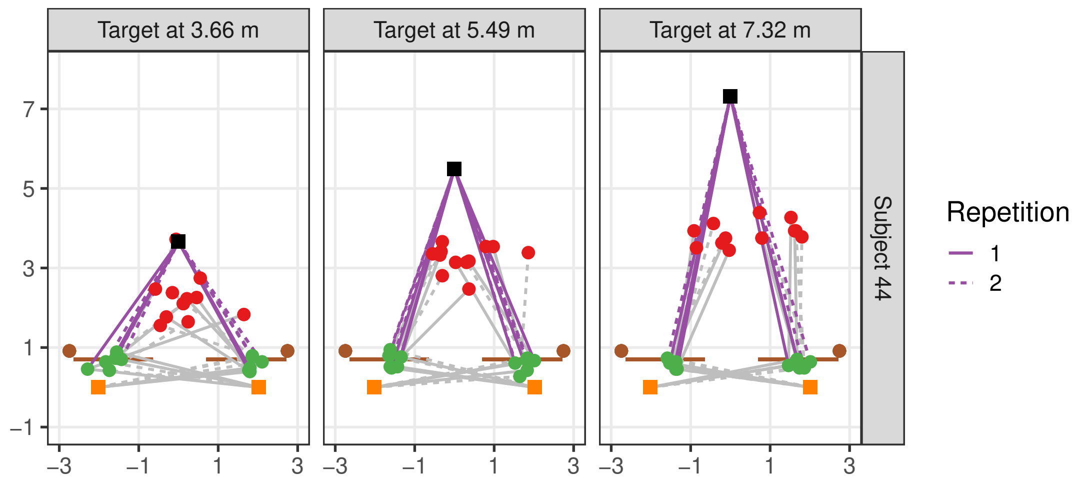
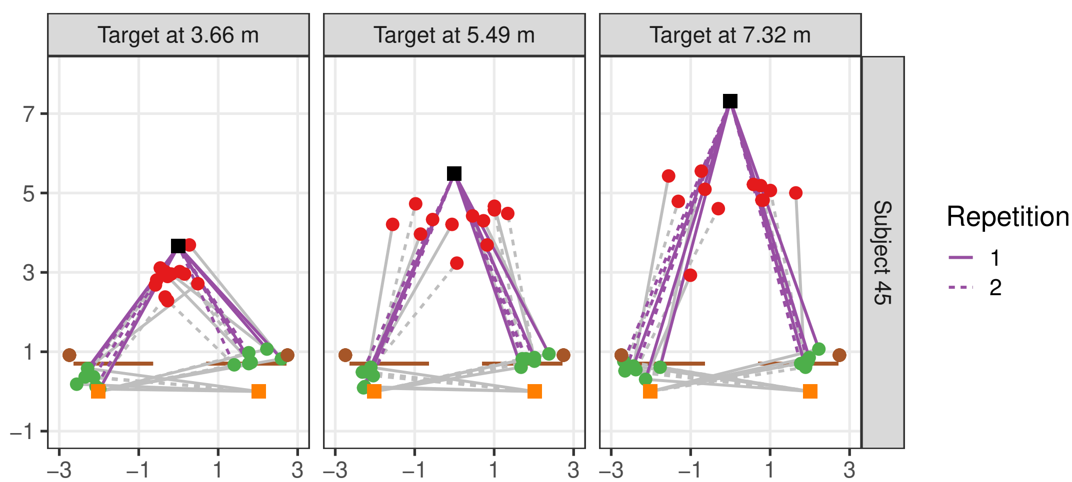

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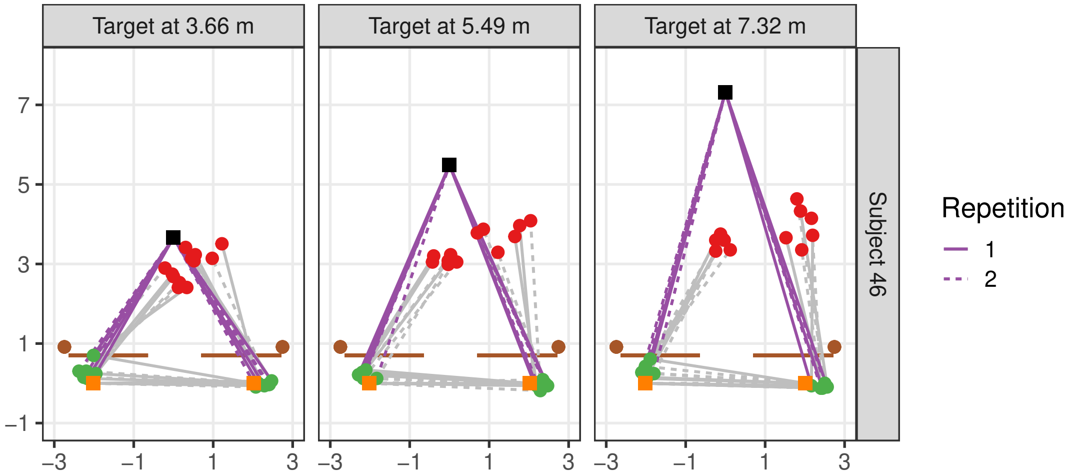
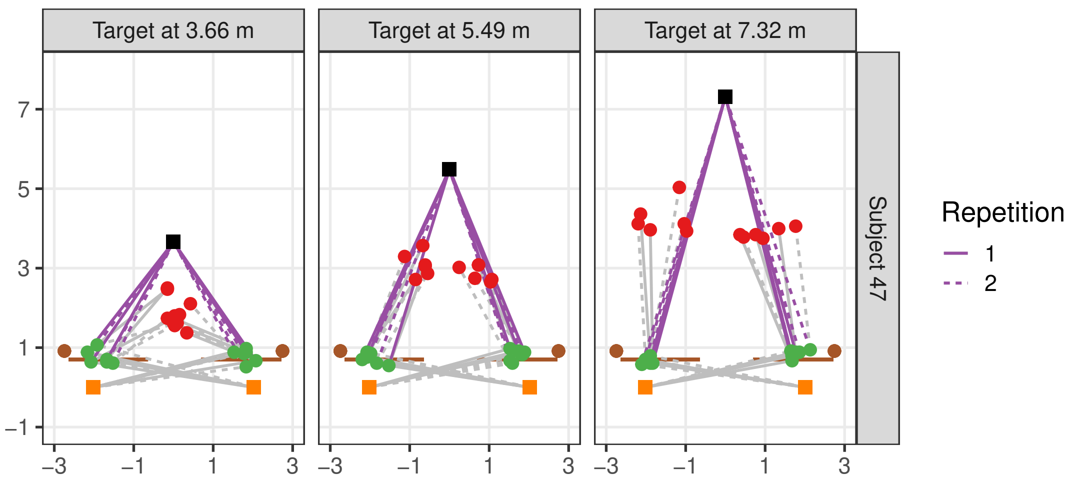

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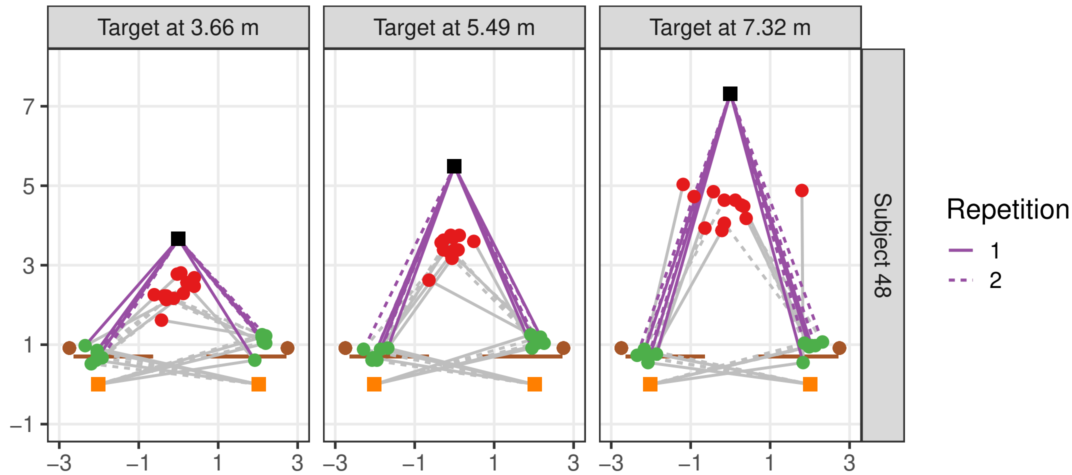
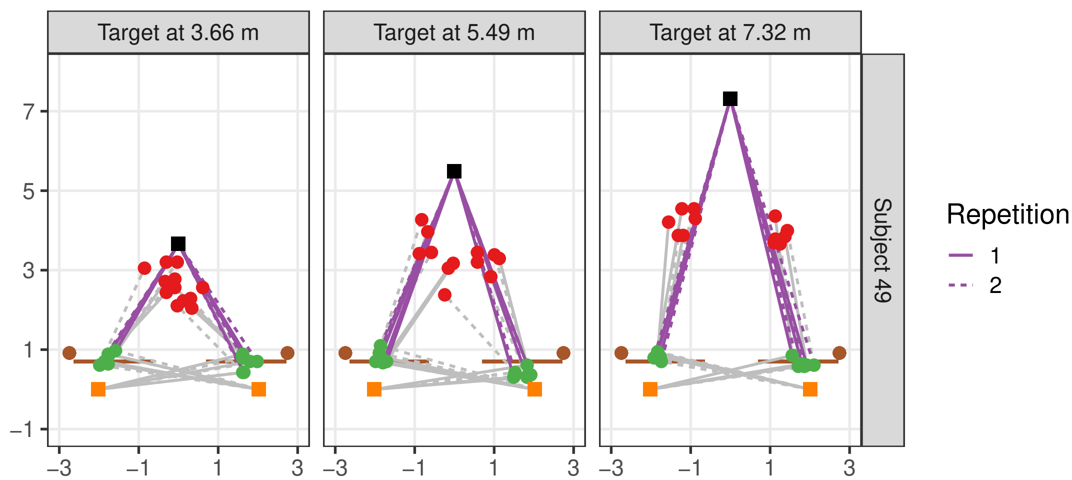
Experiment 4 Walked Paths



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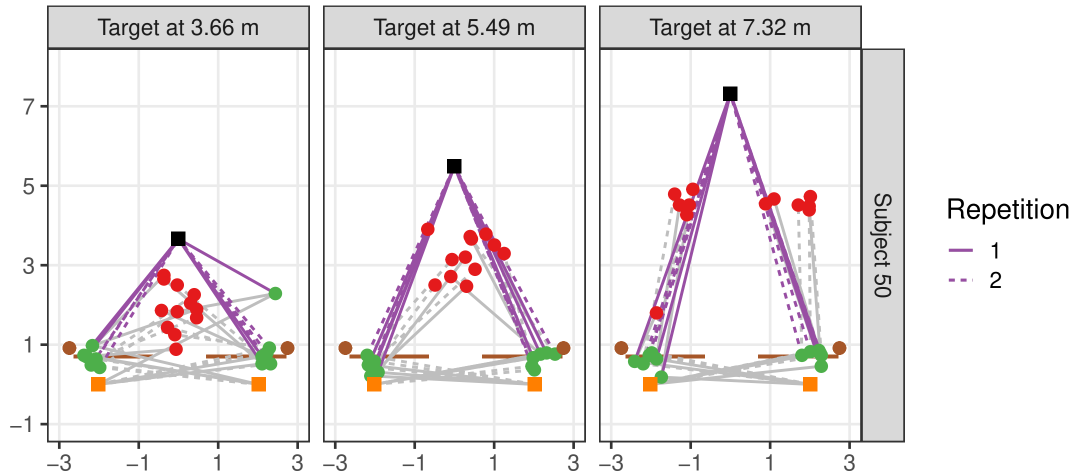
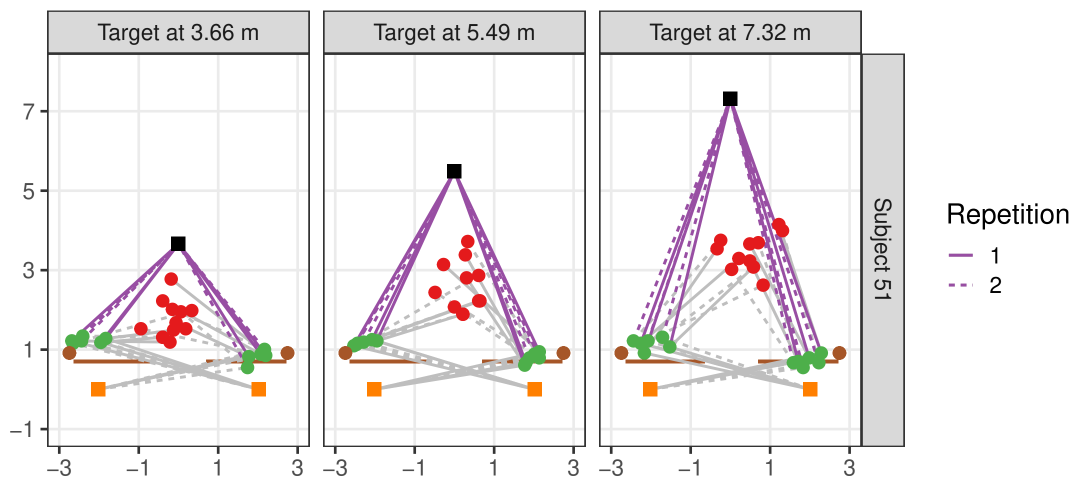

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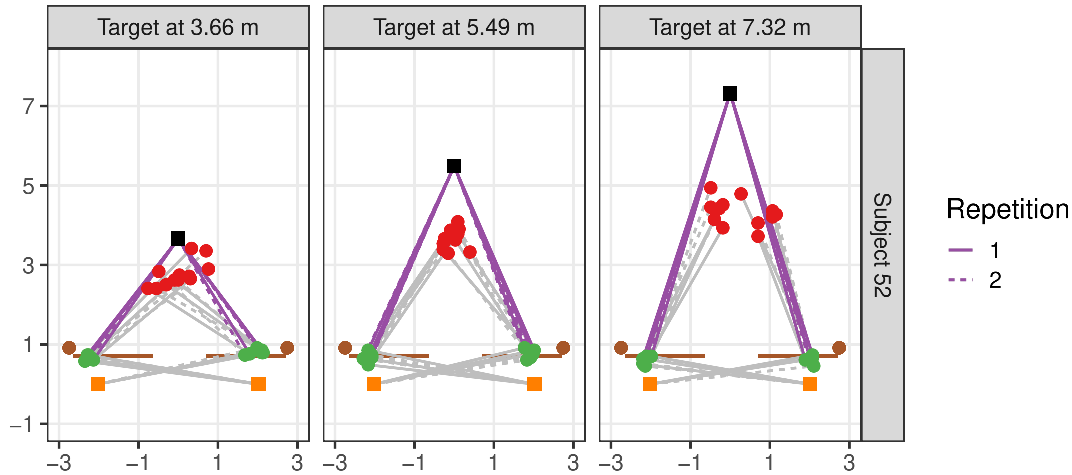
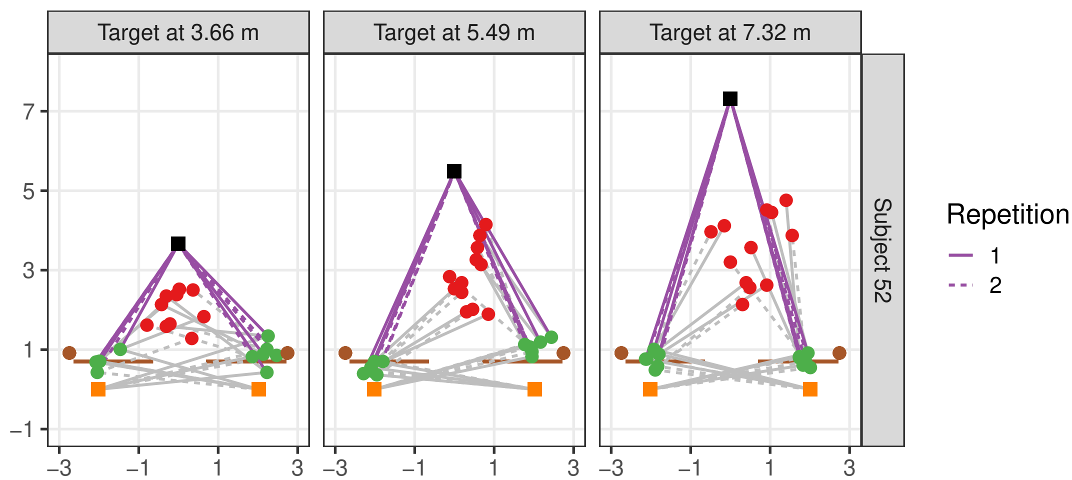
Experiment 4 Walked Paths



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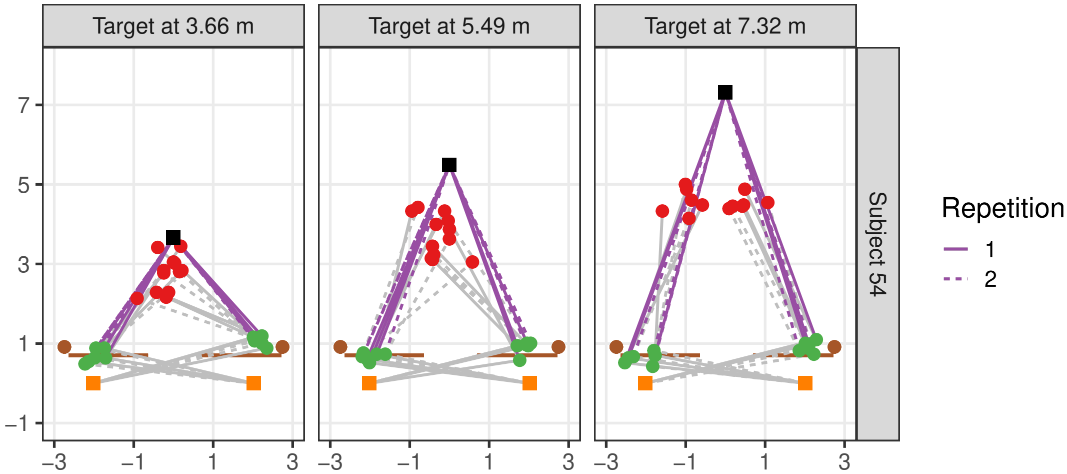
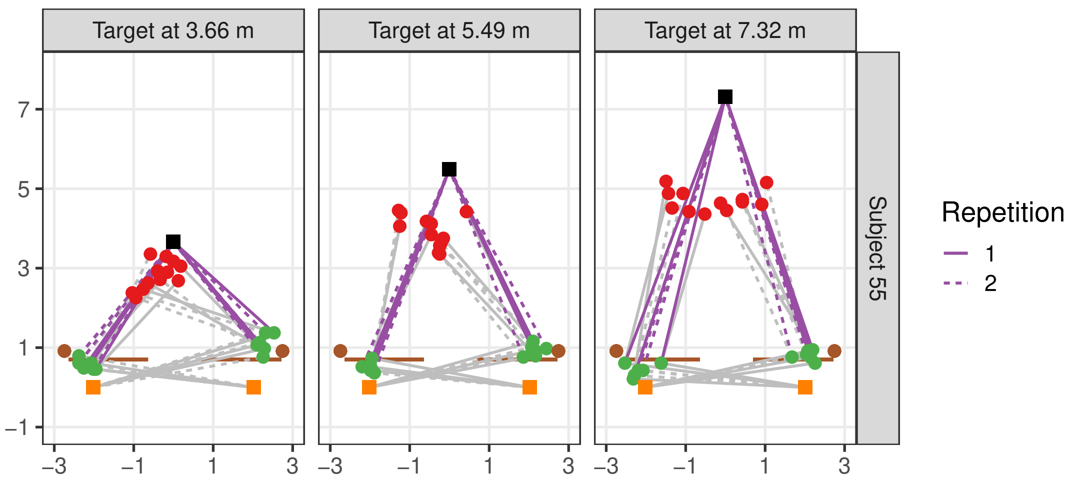
Experiment 4 Walked Paths



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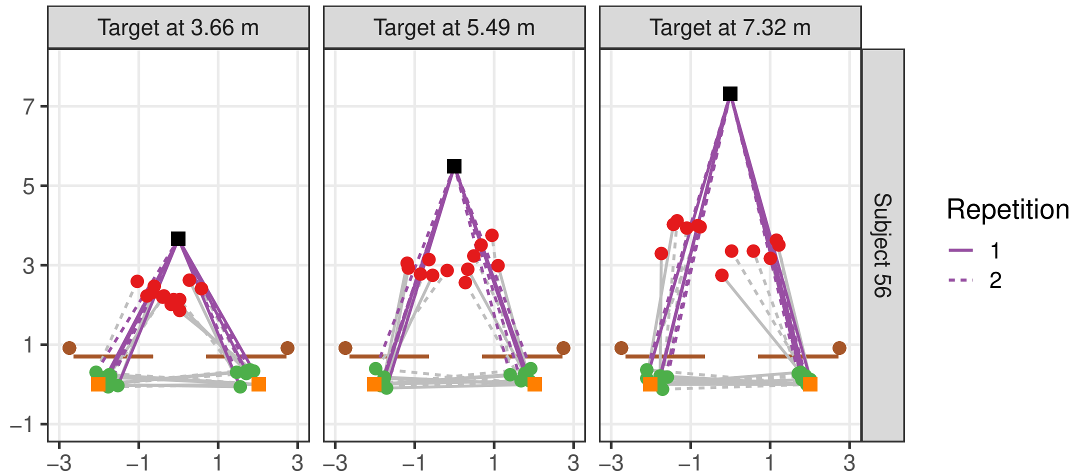
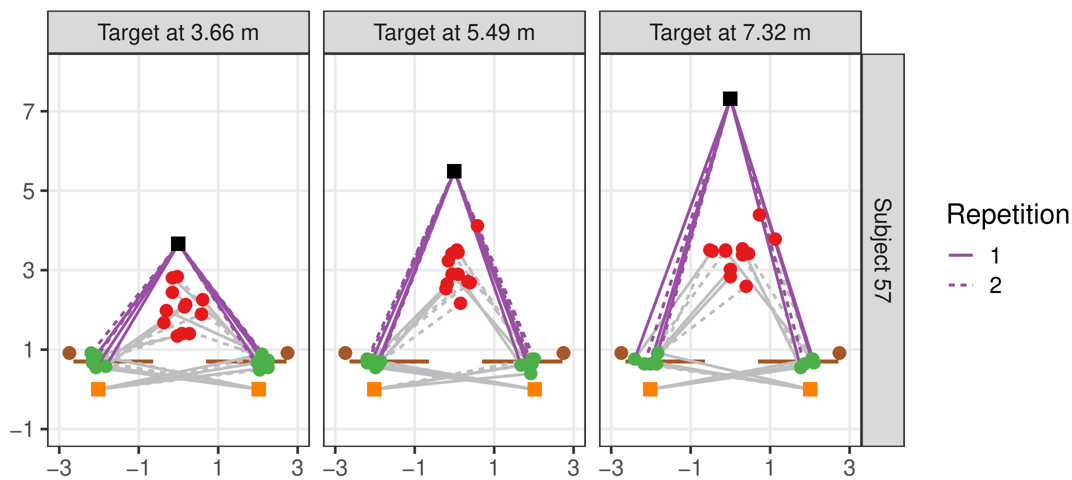
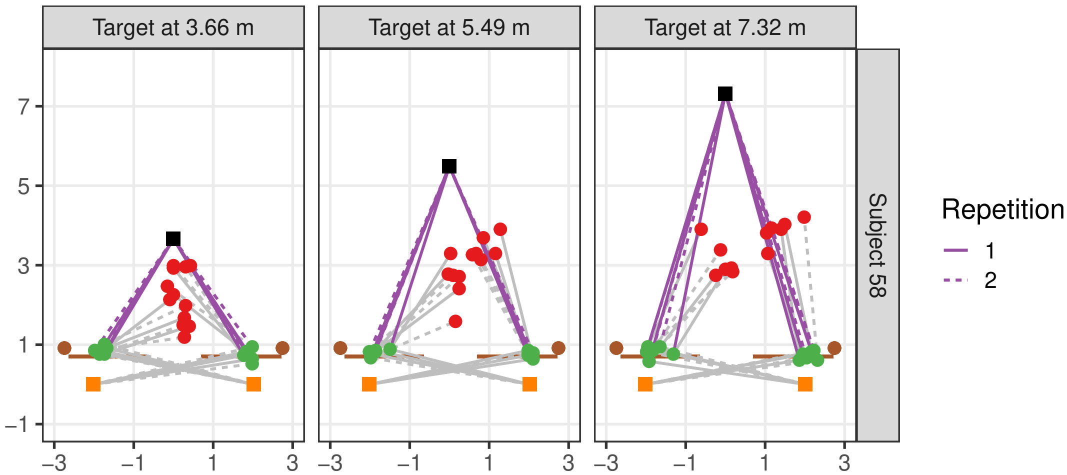
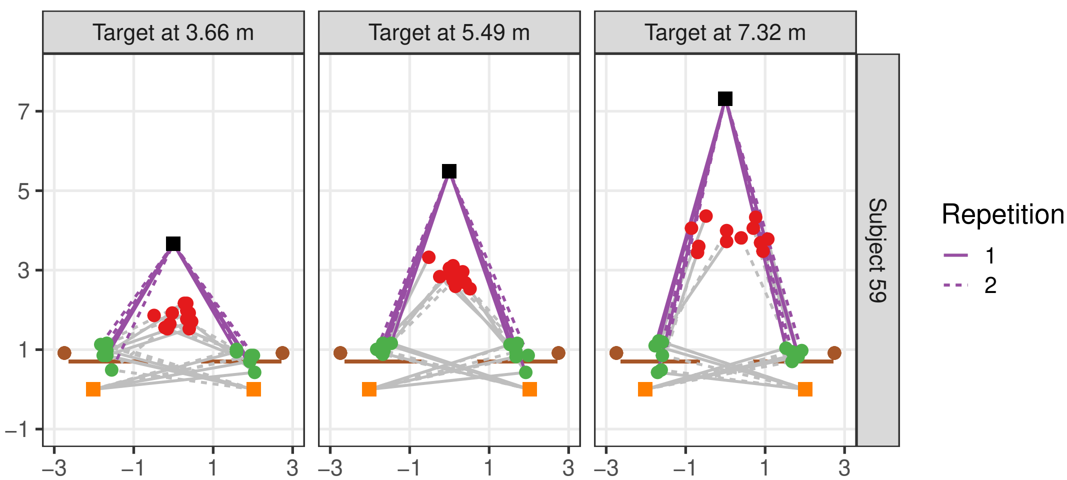
Experiment 4 Walked Paths



Continuation of Table C.4
Experiment 4 Walked Paths



Continuation of Table C.4
Experiment 4 Walked Paths

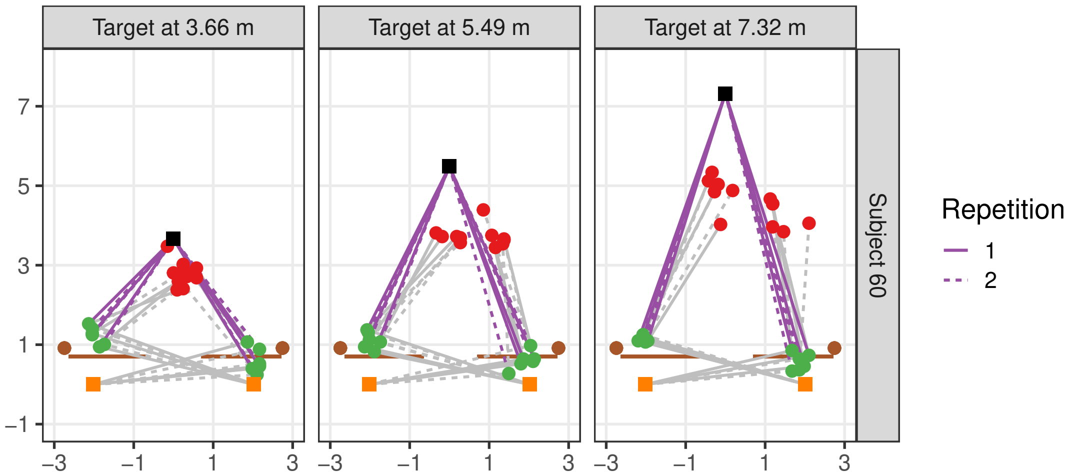
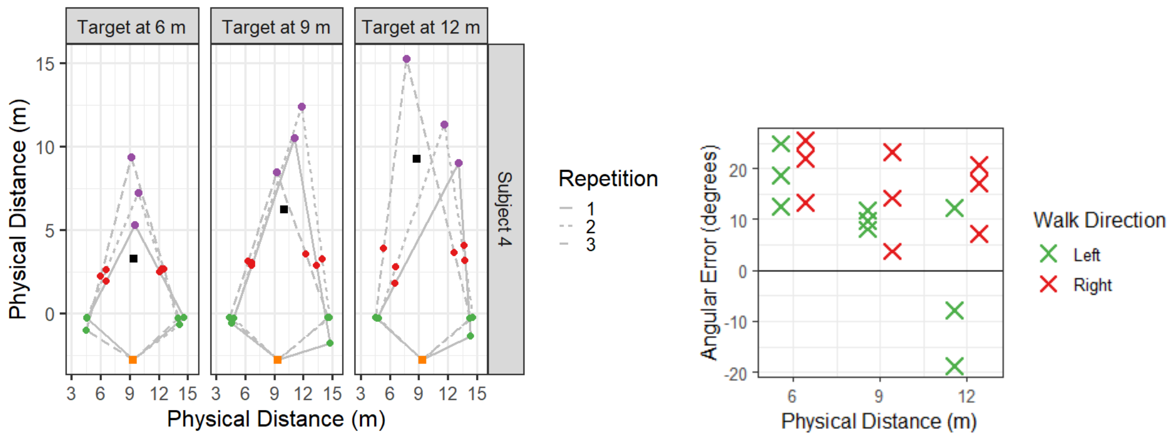


Table C.4: The walked paths of Experiment 4 ($N = 20$). The orange points represent starting location; green, turn points; brown, wood chip location; red, stop points; the purple lines, correct paths to the target; the grey lines, actual walked paths; the brown lines, wall location (Figure C.1); and the black point, target location. Target distance from the origin is labelled at the top of the graph.

APPENDIX D

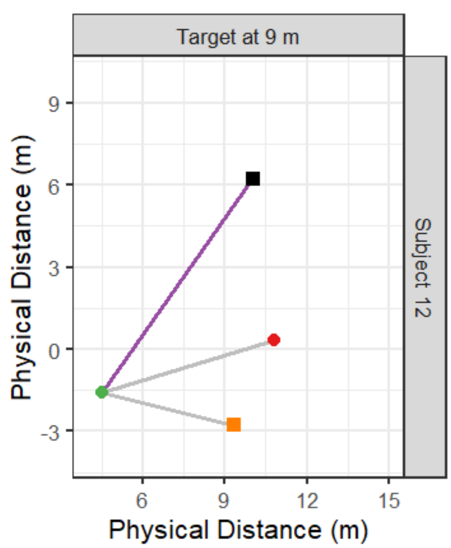
PARTICIPANT OUTLIERS

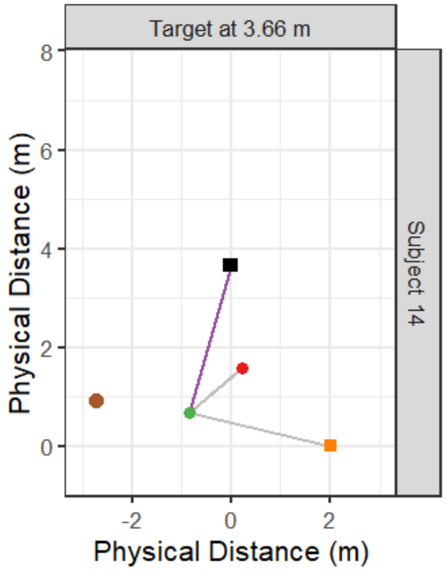
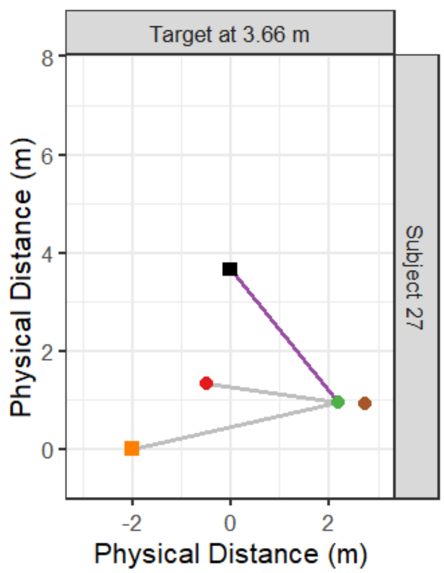


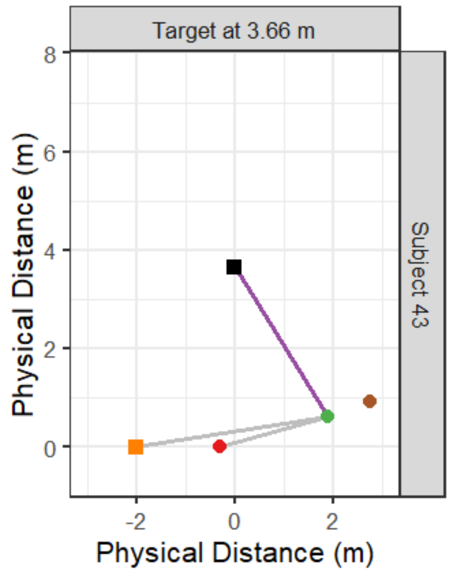
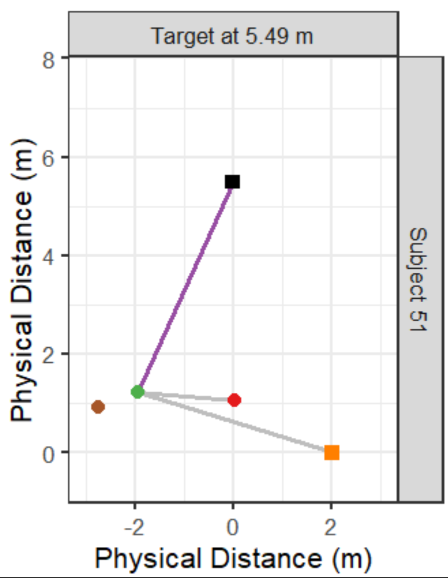
(a) Walked Path (b) Angular Error

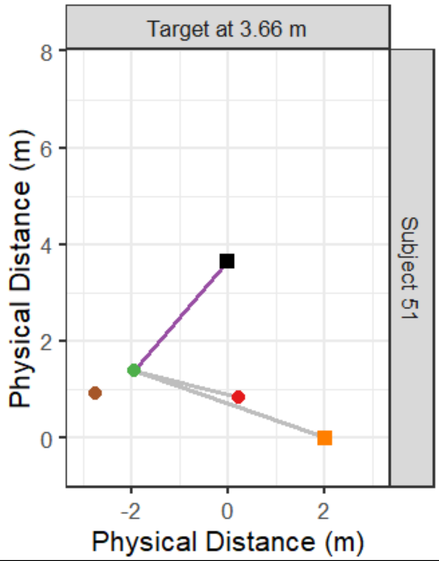
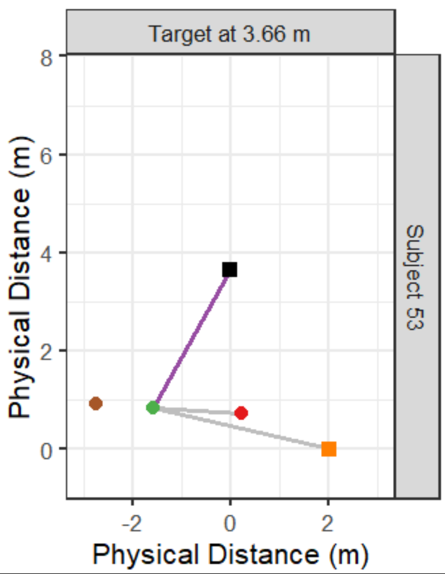
Figure D.1: Near outlier in Experiment 1. Error was high across the participant's judgments, but not enough to rise to the level of outlier.

Table D.1: Experimental Outliers

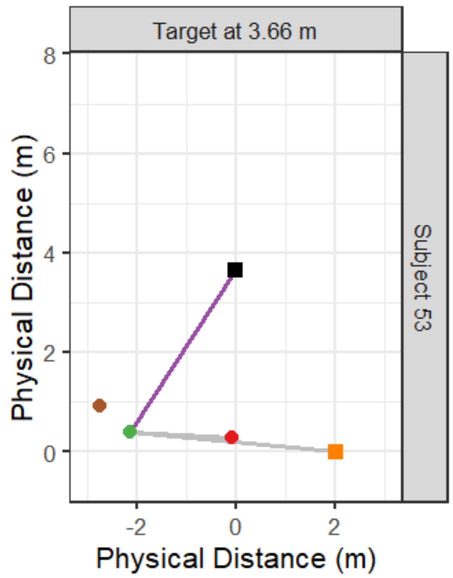
Experiment	*Outlier*	*Observed Error*
Experiment 1		**Procedural Outlier** This stop point differed substantially from the participant's other results, resulting in 38.33° of underestimation; this is thought to be the result of measurement error. Corrected by averaging the other two measured stop points for this participant at nine meters walking from the left.

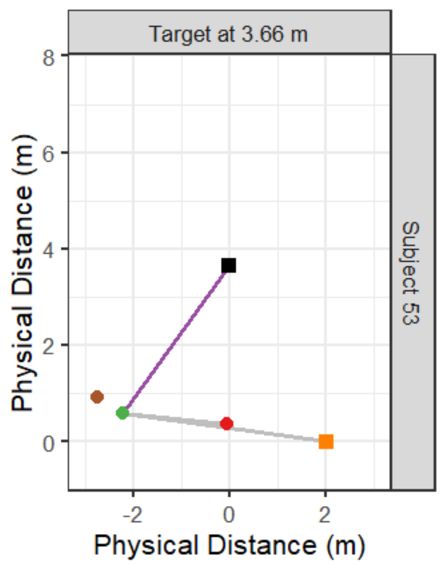
Continuation of Table D.1		
Experiment	*Outlier*	*Observed Error*
Experiment 2		**Near Outlier** The error for this data point was an underestimation of 33.45°, which was below the error outlier threshold of 50°. No corrections necessary.
Experiment 3		**Near Outlier** The error for this data point was an underestimation of 48.96°, which was just below the error outlier threshold of 50°. No corrections necessary.

Continuation of Table D.1		
Experiment	*Outlier*	*Observed Error*
Experiment 4		**Error Outlier** The error for this data point was an underestimation of 73.73°, which was beyond the error outlier threshold of 50°. Corrected by replacing the stop point with the participant's other estimated stop point for this combination of factors.
Experiment 4		**Error Outlier** The error for this data point was an underestimation of 69.83°, which was beyond the error outlier threshold of 50°. Corrected by replacing the stop point with the participant's other estimated stop point for this combination of factors.

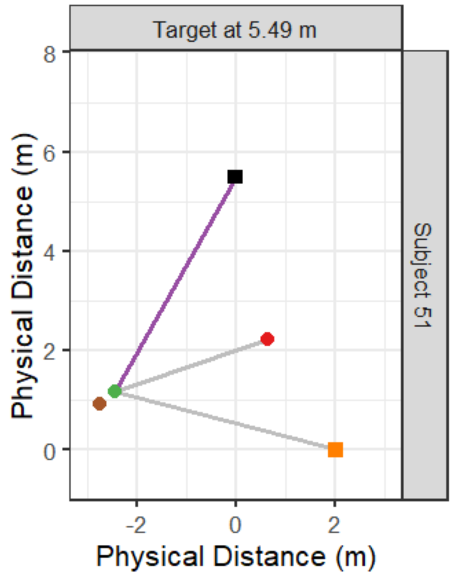
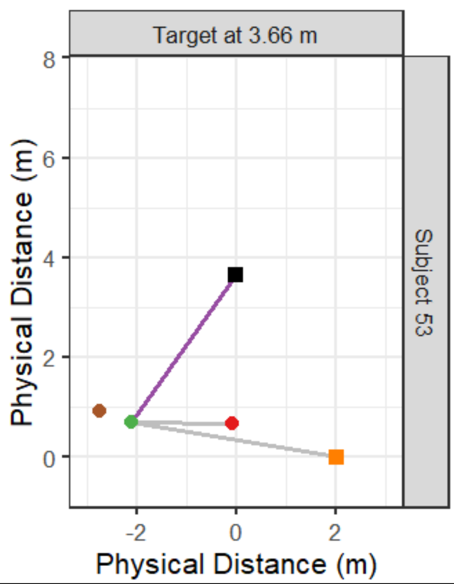
Continuation of Table D.1		
Experiment	*Outlier*	*Observed Error*
Experiment 4		**Error Outlier** The error for this data point was an underestimation of 64.13°, which was beyond the error outlier threshold of 50°. Corrected by replacing the stop point with the participant's other estimated stop point for this combination of factors and replacing the turn point with the participant's average turn point.
Experiment 4		**Error Outlier** The error for this data point was an underestimation of 63.70°, which was beyond the error outlier threshold of 50°. Corrected by replacing the turn points with the participant's average and replacing the stop points with the average over all participants for that combination of factors[1].

[1] All participant judged points for this condition//distance//walking direction were over the error threshold; therefore, the correction for this data point had to come from the average across all participants.

<table>
<tr><th colspan="3">Continuation of Table D.1</th></tr>
<tr><th>Experiment</th><th>Outlier</th><th>Observed Error</th></tr>
<tr><td>Experiment 4</td><td>
</td><td>Error Outlier

The error for this data point was an underestimation of 60.22°, which was beyond the error outlier threshold of 50°. Corrected by replacing the turn points with the participant's average and replacing the stop points with the average over all participants for that combination of factors[1].</td></tr>
<tr><td>Experiment 4</td><td>
</td><td>Error Outlier

The error for this data point was an underestimation of 59.77°, which was beyond the error outlier threshold of 50°. Corrected by replacing the turn points with the participant's average and replacing the stop points with the average over all participants for that combination of factors[1].</td></tr>
</table>

Continuation of Table D.1		
Experiment	*Outlier*	*Observed Error*
Experiment 4		**Error Outlier** The error for this data point was an underestimation of 55.90°, which was beyond the error outlier threshold of 50°. Corrected by replacing the stop point with the participant's other estimated stop point for this combination of factors.
Experiment 4		**Error Outlier** The error for this data point was an underestimation of 55.44°, which was beyond the error outlier threshold of 50°. Corrected by replacing the turn points with the participant's average and replacing the stop points with the average over all participants for that combination of factors[1].

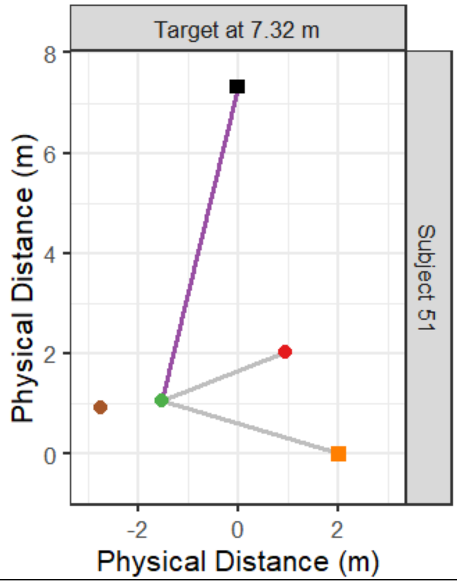
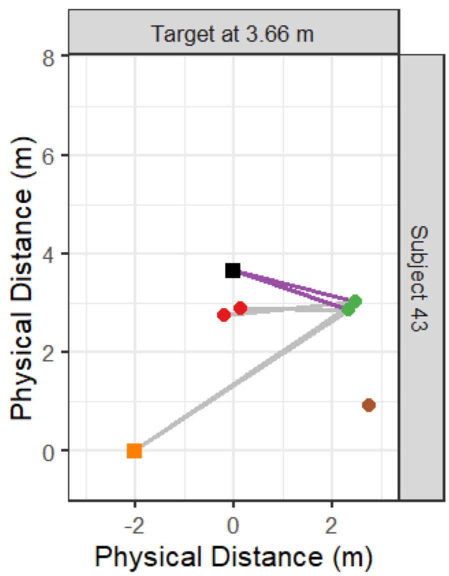
Continuation of Table D.1		
Experiment	*Outlier*	*Observed Error*
Experiment 4		**Error Outlier** The error for this data point was an underestimation of 55.35°, which was beyond the error outlier threshold of 50°. Corrected by replacing the stop point with the participant's other estimated stop point for this combination of factors.
Experiment 4		**Procedural Outlier** Two turn distances were misrecorded (for an average angular error of 19.26°). Corrected by setting the turn points to the average of the participant's other turn points from the right walking direction.

Table D.1: The walked paths of Experiment 4 ($N = 20$). The orange points represent starting location; green, turn points; brown, wood chip or experimenter location; red, stop points; purple, correct paths to the target; grey, actual walked paths; and black, target location. Target distance from the origin is labelled at the top of the graph.