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# THE IMPACT OF PRE-EXPERIMENT WALKING ON DISTANCE PERCEPTION IN VR

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# Dedication

To my beloved mom and dad,

Who have been my unwavering pillars of support and inspiration, your love and sacrifices have shaped my journey in ways words can never fully express. This thesis is a testament to your enduring belief in my dreams and the strength you've instilled in me to pursue them. From my earliest memories, your sacrifices have shaped my path. Without you, this work would have remained an unfulfilled dream.

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The contributions of everyone mentioned above were instrumental. I could not have completed this dissertation without them, and I wholeheartedly thank them.

# List of Abbreviations

| | |
|---|---|
| HMD | Head-mounted Display |
| OpenGL | Open Graphics Library |
| VR | Virtual Reality |
| PEBW | Pre-Experiment Blind Walking |

# Abstract

While individuals can accurately estimate distances in the real world, this ability is often diminished in virtual reality (VR) simulations, hampering performance across training, entertainment, prototyping, and education domains. To assess distance judgments, the direct blind walking method—having participants walk blindfolded to targets—is frequently used. Typically, direct blind walking measurements are performed after an initial practice phase, where people become comfortable with walking while blindfolded. Surprisingly, little research has explored how such pre-experiment walking impacts subsequent VR distance judgments. Our initial investigation revealed increased pre-experiment blind walking reduced distance underestimations, underscoring the importance of detailing these preparatory procedures in research—details often overlooked. In a follow-up study, we found that eyes-open walking prior to pre-experiment blind walking did not influence results, while extensive pre-experiment blind walking led to overestimation. Additionally, see-through walking had a slightly greater impact and less underestimation compared to one loop of pre-experiment blind walking. Our comprehensive research deepens our understanding of how pre-experiment methodologies influence distance judgments in VR, guides future research protocols, and elucidates the mechanics of distance estimation within virtual reality.

# Chapter 1

# Introduction

The Virtual Reality (VR) domain has made remarkable progress in recent years, separating into various sections such as education, entertainment, and training. However, certain aspects of VR still exhibit discrepancies compared to real-world tasks. Notably, distance perception in VR has been identified as an area where human perception of a virtual environment diverges significantly from reality. Users tend to underestimate distances in the near to middle range (a couple of meters to around 20 meters) that are most relevant for many VR applications because home users are often using VR in relatively small rooms. People can accurately make similar distance judgments in the real world. This inconsistency can cause issues for any application requiring accurate distance judgment, from tossing a virtual ball to walking across a virtual room without collision. Without a better understanding of distance perception in VR and an understanding of how to mitigate this problem, users may continue to be surprised by underestimations of distance for common tasks.

This thesis explores the phenomenon of distance underestimation in VR, particularly for between two to ten meters. Cutting and Vishton[8] categorize these distances as being part of "action space", which is between personal space ($< 2$ meters). Our aim is to go into the underlying reasons that lead to the perception of distances being shorter in VR than in the physical world. To achieve this, we use a commonly used technique for measuring distance perception in action space called "direct blind walking". Simultaneously, we intend to uncover potential complications associated with this technique while understanding the central issues of distance underestimation in VR.

Our research focuses on the direct blind walking task often used in VR studies to understand distance perception. In this task, participants observe a target placed on the floor in VR, then are blindfolded and asked to walk toward it. They stop walking when they believe that they are standing on the target. The distance they walked is measured and interpreted to be an indication of the perceived distance to the target. Before this experiment, participants usually practiced blind walking while wearing a blindfold. This warm-up includes safety measures, like stopping participants from collisions and guiding their walking direction. Our study aims to give a closer look at these preliminary steps, which haven't received much attention before but could significantly affect the results. By examining this, we hope to add important information to the current discussion on how distance is perceived in virtual reality. Researchers also use direct blind walking and blind walking practice prior to studies in real-world studies. The work presented in this dissertation focuses on distance judgments in VR, but the results may also be relevant to real-world distance judgment studies.

In our research about how people perceive things in virtual reality, it's important to focus on what we do before the main experiment starts. These early steps can affect the final results, so they need careful attention. However, there is little work measuring how the pre-experiment procedures might impact the study itself. Worse, many papers don't report what procedures they performed prior to the study or provide limited details. This is not just about showing what we found out; it's also about making sure others can repeat our work to check it. If different research teams don't use the same pre-experiment procedures, they could get different results even when they're studying the same thing. Similarly, if studies do not report pre-experiment procedures in detail that could impact results, it is difficult to interpret and compare studies. This helps the scientific community better understand the study, compare it with other studies, and better understand how virtual reality changes how we perceive things.

## 1.1 Contribution

One of our key aims is to examine how variations in the pre-experiment setup for studying distance perception using direct blind walking can influence the findings. Our work answers multiple questions, such as: Is there a difference between doing a long or short amount of pre-experiment walking? Does the amount of walking matter because it involves people walking or because they are also doing it with their eyes closed? Does the amount of walking the participant did prior to showing up for a study impact the results? This work does not aim to specify the 'perfect' procedure everyone should follow. Instead, we try different approaches to the setup and observe how these changes affect the results. This information can help other researchers decide how precise they need to be in their own setups. Beyond just procedural concerns, our work also sheds light on how previous walking experiences can impact how people judge distances in direct blind walking experiments.

Additionally, this study examines how different types of pre-experiment walking can influence the results of an experiment. Three types of walking interest us: blind walking, open-eyes walking, and see-through walking, which allows users to view the real world through their VR headsets from the real world. The see-through walking technique might be interesting because it's not well studied yet, but it could potentially have a huge effect on how people perceive distances. In VR, we hope to understand better the effects of these different types of walking by comparing them.

## 1.2 Organization

In Chapter 2, we outline the history of distance judgments in VR and survey the commonly used methods for distance measurement. We also explain our motivations for concentrating on the direct blind walking method.

In Chapter 3, we present our first experiments concerning the influence of the pre-experiment blind walk (PEBW) on distance perception. We also investigate how adjusting the duration of this task could influence the perceived distance in VR experiments.

Chapter 4 responds to certain questions that emerged from our preliminary studies and explore the analysis of the See-Through mode's impact on perceived distance during the experiments.

In Chapter 5, we describe the algorithm developments related to Chapter 4.

Finally, in Chapter 6, we summarize our findings and our work on this dissertation. We also discuss future research directions and acknowledge the limitations of our current study. This provides a comprehensive conclusion that outlines our contributions, as well as paths for future exploration.

# Chapter 2

# Background and Related Work

## 2.1 Background VR Technology and Distance Perception in VR

The technology of virtual reality (VR) has advanced rapidly over the last few years, creating increasingly immersive and realistic virtual environments [32, 33, 60]. As a result, VR applications are being used more frequently across various fields, including training, education, entertainment, and prototyping [3], [49]. A key goal is to enable users to perceive and interact within virtual environments consistently with their real-world experiences, creating compelling and believable VR [57]. This requires ensuring spatial judgments and distance estimates match real-world accuracy as closely

**Figure 2.1:** A VR user in a laboratory

as possible [29]. Our work is focused on one type of distance judgment called "ego-centric" distances, where people must judge the distance between themselves and an object in the environment. In the real world, humans tend to be proficient at judging egocentric distances in the critical range for many applications [12, 39, 51]. The aim of VR is to create a system where user performance in VR matches their performance at an equivalent task in the real world. This calibration is particularly challenging but crucial for industries like the military and aerospace that increasingly use VR technologies for essential training operations [4], [30]. Having VR distance perception aligned with real-world experiences helps maximize training accuracy and skill transfer from virtual to physical environments.

## 2.2 Limitations of VR Technology

One excellent resource for learning about distance judgments in VR and the real world is a comprehensive survey article by Renner et al. [43], which summarizes the results of much of the work in the VR and real world distance judgments prior to 2013. It identifies four primary categories influencing distance perception in VR: technical, compositional, human factors, and measurement methods. While technical and compositional elements like display resolution and environmental design and measurement methods such as different types of distance perception measurement methods have been extensively studied, the human factor remains comparatively less explored. Given this gap, my research aims to fill it by focusing on the role of PEBW in distance perception in VR. This human factor is particularly pertinent as it has shown inconsistencies in its application across different studies, further complicating our understanding of distance perception in VR.

Extensive research has demonstrated that egocentric distances are often underestimated in VR, particularly when using Head-Mounted-Displays (HMDs) [9, 43, 52]. This underestimation is not just an isolated issue but is compounded by inconsistencies in the methodologies employed by researchers, particularly regarding PEBW. Some studies do not mention PEBW at all [15, 22, 34], while others specify varying durations [7, 9, 24, 38]. These inconsistencies introduce ambiguity in methodology and create challenges in comparing results across studies. We have summarized older studies up to recent studies regarding distance judgment in VR in Table 2.1. This table includes crucial data from each study, such as their estimated distance in each study, whether they have done PEBW or not with what durations, and the type of VR HMDs they have used in their experiment. Based on the summary studies table in Table 2.1, studies that explicitly report using PEBW have an average perceived distance around 80% in contrast to 74% in studies that did not have or did not explicitly mention PEBW in their experimental procedure for distance estimation with the direct blind walking method, thus underscoring the influence of this human factor on distance perception outcomes. Although we suspect that some papers may have used PEBW without reporting it, these results support the idea that perhaps PEBW does have a significant impact on distance judgment studies.

**Table 2.1**
Summary of previous VR distance perception studies using Direct Blind Walking

| **Paper [Year]** | **HMD Model** | **PEBW** | **Dist. (m)** | **%** |
|---|---|---|---|---|
| Kelly et al. [2022] [22] | Oculus Quest 1 and 2 | Unknown | 1 to 5 | 68-70% |
| Sepahyar & Kuhl [2022] [48] | Oculus CV1 | Yes, 0-4 loops 3 to 6 mins | 2 to 5 | 80-97% |
| Masnadi et al. [2021] [31] | Pimax 5K Plus | Unknown | 3 to 6 | 95-100% |
| Ding et al. [2020] [9] | Oculus CV1 | Yes, several mins | 2 to 5 | 88% |
| Li et al. [2018] [27] | Oculus DK2 | Yes, several mins | 2 to 5 | 72-93% |
| Kelly [2018] [21] | NVis SX111 | Unknown | 1 to 5 | 71% |
| Siegel et al. [2017] [50] | NVis SX111 | Unknown | 1 to 5 | 63% |
| Kelly [2017] [20] | NVIS nVisor ST50 | Unknown | 1 to 5 | 65% |
| Kelly [2017] [20] | NVis SX111 | Unknown | 1 to 5 | 64% |
| Kelly [2017] [20] | HTC Vive | Unknown | 1 to 5 | 84% |
| Li et al. [2015] [26] | Oculus Rift DK2 | Yes, Several mins | 2 to 5 | 89% |
| Creem-Regehr et al. [2015] [7] | Oculus Rift DK2 | Yes, 5 mins | 3 to 6 | 86% |
| Creem-Regehr et al. [2015] [7] | NVIS nVisor SX | Yes, 5 mins | 3 to 6 | 69% |
| Kelly [2014] [19] | NVIS nVisor ST50 | Unknown | 1 to 5 | 60-65% |
| Kelly et al. [2013] [18] | NVIS SX111 | Unknown | 1 to 4 | 70% |
| ZHANG et al. [2012] [59] | NVIS nVisor ST | Yes, Several mins | 2 to 5 | 76% |

Continued on next page

Table 2.1 – continued from previous page

| **Paper [Year]** | **HMD Model** | **PEBW** | **Dist. (m)** | **%** |
|---|---|---|---|---|
| Jones et al. [2011] [16] | NVIS nVisor ST | 5 practice trials | 1 to 4 | 65-75% |
| Ahmed et al. [2010] [1] | Z800 3DVisor by EMagin | Yes, until comfortable | 2 to 5 | 91% |
| Grechkin et al. [2010] [13] | NVIS nVisor ST | Unknown | 6 to 18 | 70% |
| Kunz et al. [2009] [25] | NVIS nVisor SX | Yes, 5 min | 3 to 6 | 78-83% |
| Willemsen et al. [2009] [55] | NVIS nVisor SX | Unknown | 4 to 8 | 63% |
| Kuhl et al. [2009] [24] | NVIS nVisor SX | Yes, Several mins | 3 to 6 | 63-98% |
| Mohler et al. [2007] [38] | Big Screen | Yes, 5 mins | 6 to 10 | 94-111% |
| Interrante et al. [2006] [15] | nVis nVisor SX | Unknown | 2 to 7 | 88-93% |
| Kuhl et al. [2006] [23] | NVIS nVisor SX | Yes, Several mins | 3 to 6 | 83% |
| Richardson et al. [2005] [44] | V8 | Yes | 1 to 4 | 76% |
| Messing & Durgin [2005] [34] | V8 | Unknown | 2 to 7 | 70-75% |
| Sahm et al. [2005] [47] | NVIS nVisor SX | Yes, 5 mins | 3 to 6 | 70% |
| Willemsen et al.[2004] [54] | NVIS nVisor SX | Yes | 4 to 8 | 63% |
| Willemsen et al. [2002] [53] | nVision Datavisor HiRes | Yes, 5 mins | 2 to 5 | 60-80% |
| Witmer et al. [1998] [56] | BOOM2C | Unknown | 5 to 32 | 85% |

## 2.3 Distance Perception Measurement Techniques

It is impossible to measure perceived distance directly. Any attempt to measure how people perceive distances requires asking people to communicate or perform some action based on the perceived distance. Since it is possible that the measurement technique itself might produce biased results that are not representative of the actual perceived distance, it is good that the distance perception literature contains many examples of studies using different techniques. Among the techniques used in the literature, verbal reporting and direct blind walking stand out for their simplicity and relevance to our work.

In verbal reporting, participants are asked to verbally report the perceived distance of objects or surfaces within the VR environment, which is then compared to the actual distances. This method is quick and straightforward and has been widely used in many studies investigating distance perception in virtual, augmented, and real environments [25, 58]. However, its subjective nature can make interpretation challenging, and participants tend to round their answers or might not be familiar with different units, such as meters or feet, even if participants can select their preferred unit. Some participants might also view the task as more of a math or geometry problem, even if they are instructed not to. Verbal reports also often lead to distance underestimation in VR compared to the real world. However, some differences between the techniques

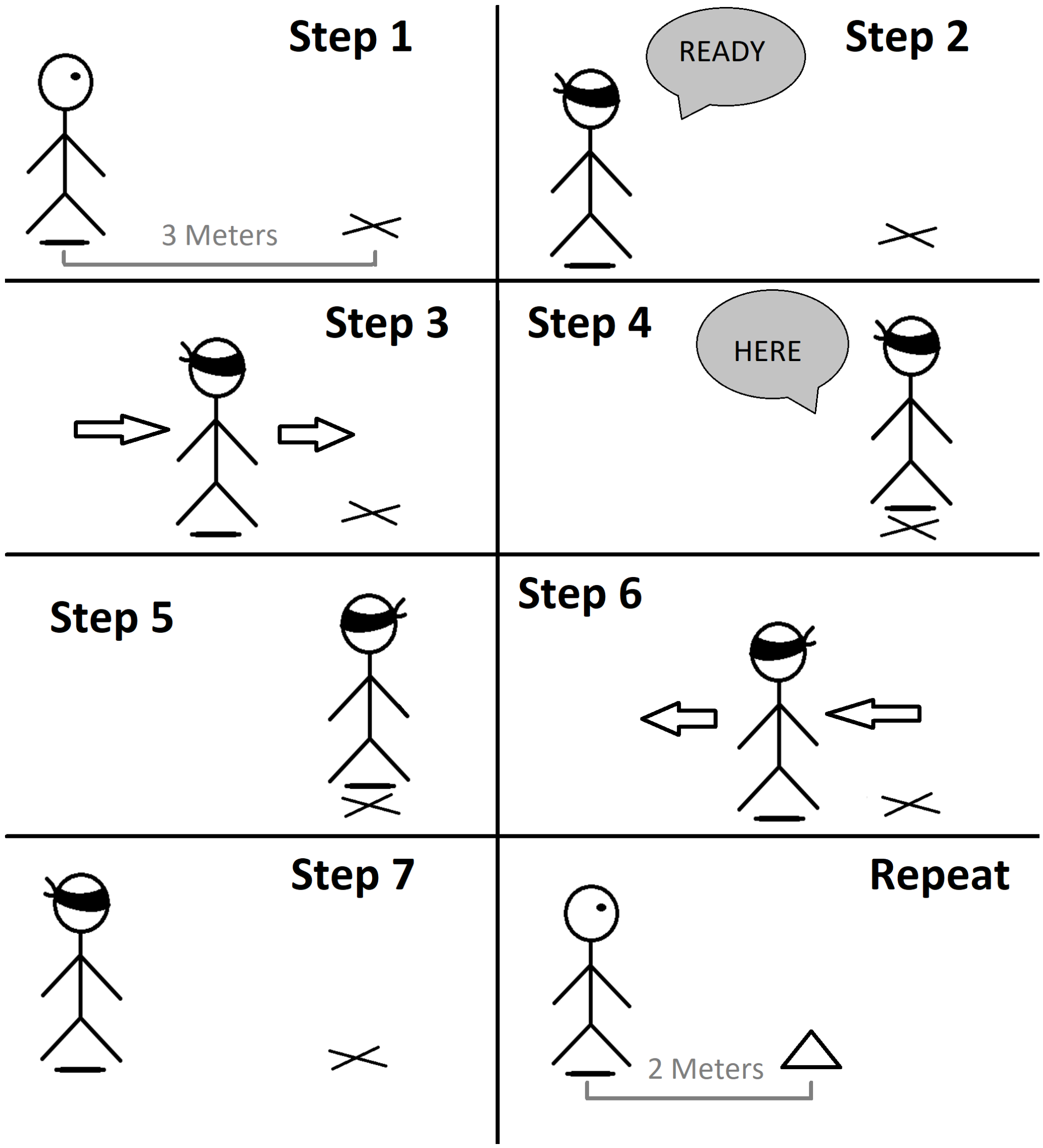


**Figure 2.2:** Direct blind walking procedure

have been discovered. For example, [25] found graphical quality influences verbal reports of perceived distance but does not significantly impact direct blind walking results.

Direct blind walking is another commonly utilized technique in VR, Augmented Reality, and real-world experiments. Participants observe a target within the real or virtual world, depending on the study and experiment, and then, while blindfolded, walk to the perceived target location. The complete steps of the direct blind walking task are shown in Figure 2.2. They are instructed to stop walking when they think that they are standing on the target (in real-world studies, the target is moved out of the way before they reach it so they cannot feel it under their feet). This method provides a non-verbal, direct, and intuitive way to assess spatial perception and estimate distance in VR. Whereas verbal reports are an uncommon activity, walking to a previously seen object while looking elsewhere is also a common task, and direct blind walking is loosely similar to that. Direct blind walking is also the most commonly used method. Many direct blind walking experimental results are summarized in Table 2.1.

There are also a variety of alternative methods used in the field. For instance, indirect blind walking involves observing a target in VR and then performing an action that does not involve directly walking to the target. For example, participants could view a target in a virtual environment in a small laboratory, then remove the headset, blindfolded, taken to a larger space, and asked to walk to the target. This process is the same as direct blind walking, but participants are walked to a different location before doing the walk that is measured. This provides an objective measure of spatial perception but could be influenced by discrepancies between real-life and virtual movement [5, 28].

One popular indirect method, triangulated walking, involves moving along two sides of a triangle in VR to reach a target. In this case, people view the target, turn some amount left or right, then walk a short distance. After some distance, the experimenter asks the participant to point at the target or take a step toward the target. This information can then be used to calculate the perceived distance to the target. This method is especially useful for longer-distance targets presented in a VR lab that has limited space. However, the cognitive complexity of this method can pose challenges [45, 52]. Also, small pointing errors can potentially result in relatively large changes in the distances the participants indicate, especially for long target distances.

Lastly, there are also a variety of less popular methods. Blind throwing is another technique that involves estimating the distance to a target in VR and then throwing a beanbag at it while blindfolded in the real world. This method allows for objective assessment of participants' spatial perception but can be affected by individual throwing abilities and potential discrepancies between real-world and virtual actions [47]. Other investigated methods include rope pulling [2, 41] and imagined walking [42].

As seen in Table 2.1, direct blind walking is the most popular method. It is commonly used in distance perception research for several reasons. First, the procedure is straightforward to explain to participants, and it does not have additional requirements besides a sufficient amount of walkable space and a way to measure the distance walked. Furthermore, this technique does not require familiarity with different unit limitations that methods such as verbal reporting have. In the context of this research, particular emphasis is placed on the direct blind walking method due to the popularity of this method among other methods and its straightforwardness to simulate distance judgment in VR as an action-based method.

One commonly asked question is why we do not provide feedback after direct blind walking to show participants how accurate they were. If people can see that they misjudge the distance, they might then be able to adjust their subsequent distance judgments to become more accurate and this kind of adaptation is known to work by Mohler et al. [36]. Nonetheless, there are several reasons why we provide no feedback during direct blind walking distance judgments: First, it may be infeasible or awkward to ensure that people are properly trained prior to using the VR system, especially if accurate distance judgment is simply desired, but not required. Second, training people to perform better in the VR environment creates a risk that it may transfer to the real world and cause worse performance in the real world. Third, training people to perform accurately is a workaround which does not help provide more insights into why distance underestimation occurs in the first place. These reasons are likely feedback is often not used in the existing literature. Overall

## 2.4 Inconsistencies in Direct Blind Walking Task In VR

Despite the advantages of the direct blind walking method, certain prerequisites must be satisfied for successful implementation in VR experiments. PEBW is one such step, designed to allow participants to adapt to the act of blindfolded walking, thereby enhancing their comfort and proficiency [7, 9, 24].

The use of PEBW is remarkably inconsistent across studies, casting some doubt on the reproducibility and comparability of VR distance perception research. For instance, although we examined a wide range of recent studies from diverse research groups in Table 2.1, studies regarding the information provided on PEBW were limited. Some studies don't mention PEBW at all [13, 22, 50], while others vaguely state 'several minutes' without further elaboration [9, 27]. Even in studies that seem to offer the most detail, such as Mohler et al. [38], the reported 5 minutes of PEBW lacks context. Critical aspects like the total distance covered, the width of the walking space, or even the specific instructions given to participants are often omitted. This lack of detailed reporting hampers the field's progress, as it not only prevents reproducibility but also leaves researchers guessing about the actual impact and necessity of PEBW. The primary focus of our research is to bring clarity and uniformity to the use and reporting of PEBW in VR distance perception studies.

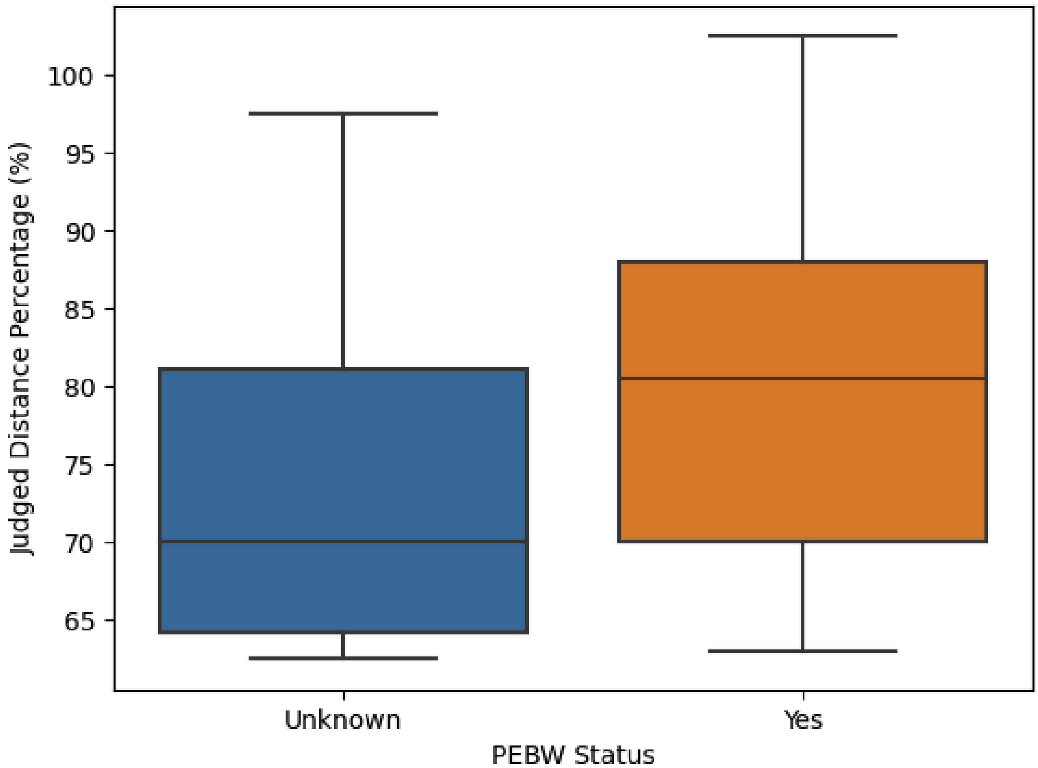


**Figure 2.3:** Box Plot of Judged Distance Percentage by PEBW Status

Our analysis of previous studies revealed an interesting trend: experiments that clearly reported using PEBW showed less distance compression on average than those that did not mention PEBW. It is important to note that it is possible that some studies did use PEBW but didn't mention it in their publication. This pattern is somewhat clear in the summarized data in Table 2.1 and the plot of estimated distance regarding their PEBW status in Figure 2.3. Studies that conducted PEBW had somewhat higher accuracy on average. These results demonstrate the importance of reporting whether PEBW was performed and the details of the procedure for experiments using blind walking for distance perception experiments. However, we need to clarify that the 5% accuracy on average for PEBW status is not something we can strongly rely on, and there are no obvious differences.

Our goal is not to establish a definitive standard for pre-experiment procedures; rather, our goal is to offer a comprehensive set of information to help researchers make informed decisions when designing their studies. We recognize that regularizing PEBW might be beneficial but may also be impractical for certain applications that cannot allocate extensive time for their experiment and research during their procedures. It's worth noting that the current variance in applying PEBW does not come from an ongoing disagreement in the field. Instead, it's due to the lack of attention to these details for the experimental procedures and how important it is to do PEBW and procedures prior to their experiment. Researchers often follow PEBW or overlook the significance of PEBW, leading to inconsistencies that hinder the interpretations and comparability of results across studies. As such, there is a clear need for more transparent and possibly more flexible procedures when utilizing direct blind walking in VR studies.

## 2.5 Influence of Environmental Changes on Distance Perception

In terms of real-world distance judgments study, the effect of walking conditions on perceived distance is essential. While the majority of studies have not investigated the impact of pre-experiment procedures on distance perception in VR, some real-world experiments provide insight into how various walking conditions, such as blind walking, can influence distance judgment. One such study by Philbeck et al. [40] serves as a starting point for this exploration and suggests that the condition of walking may indeed matter. In the context of our research, this study could offer hints regarding the influence of PEBW.

In their real-world experiment, Philbeck et al. [40] investigated the effect of blind walking on distance judgment. They discovered that participants' walked distances tended to increase over trials when they were exposed to 3 minutes of blind walking prior to the experiment compared to eyes-open walking. This indicates a recalibration effect in participants after blind walking. On average, participants undershot distance with 3.38% accuracy and overshot the target distance by 4.4% after being exposed to blind walking prior to the experiment. This experiment replicated a similar procedure using verbal reporting. However, since this overestimation did not impact verbal reporting results, it suggests that the act of blind walking influences actual walking performance rather than verbal judgment or perception abilities. In a subsequent study, Experiment 2, Philbeck et al. aimed to understand better the recalibration process observed in Experiment 1, particularly the overestimation observed during the experiment after the pre-experiment blind walk. This experiment also aimed to evaluate the impact of higher cognitive factors such as familiarity and confidence on participants' results. Thus, participants engaged in a series of marching and blind walking tasks. Over these blind walking trials, participants progressively increased their estimated distances, reaching an overestimation of approximately 10% after 37 blind walk trials. Concurrently, their walking velocity increased from 0.95 m/s to 1.1m/s, and their average pace length grew from 0.6 meters to around 0.7 meters. These findings demonstrate that participants tend to overestimate distance following a blind walking task. The researchers then attempted to differentiate between the adaptation effect caused by increased familiarity with blind walking and the recalibration of self-motion perception resulting from the mismatch situation between locomotor activity and the absence of visual information. They did this by allowing participants to walk with vision for 10 minutes. However, the results did not definitively isolate the effects of adaptation and familiarity. The researchers suggested that both factors seemed to play significant roles in the observed overestimation. Specifically, drifting, the unintentional deviation from a direct path during the trials, increased after the blindfolded trials. This suggests that the mismatch between physical motion (locomotion) and the absence of visual cues may lead participants to recalibrate their perception, leading to overestimation. Participants adjusted their response strategies over time, potentially to improve accuracy as they became more familiar with the task.

Philbeck et al. [40] showed that additional practice with blind walking enhances distance judgment accuracy, attributing this to increased confidence and adaptation. However, we know little about how this might apply to VR distance judgments where distances are often compressed. Since Philbeck et al.'s Experiment 1 also didn't investigate how different durations of pre-experiment walking might impact results. In VR, if pre-experiment walking does impact distance judgments, we are particularly interested in quantifying how much walking might be necessary to reach performance consistent with the real world. My work in this dissertation aims to extend this investigation of blind walking and distance perception into VR contexts using HMDs. Through a series of experiments manipulating pre-experiment blind walking durations, I examine whether similar patterns of adaptation and reduced underestimation emerge following increased blind walking exposure. My dissertation research pays particular attention to documenting the pre-experiment procedures, seeking to elucidate the relationship between prior walking experience and subsequent distance judgments in immersive virtual environments and deliver new empirical insights and identify key areas for further inquiry regarding the complex relationship between blind walking and distance perception in VR.

Rieser et al.'s [46] work in 1995 offers an interesting background to the recalibration effects observed in blind walking studies like that of Philbeck et al. [40]. While Philbeck et al. focused primarily on the recalibration effects of blind walking, Rieser et al. studied the mechanisms regarding how participants adjust their walking behavior in response to different visual and biomechanical conditions. Notably, their experiments changed the visual flow and biomechanical rate of walking during the adaptation phase when participants could see. Mismatched visual flow refers to the discrepancy between the speed of our physical movement and the visual cues we receive from the environment. For example, if we are walking on a moving sidewalk that is going faster or slower than our walking speed, the visual flow is mismatched (visually faster or slower conditions) with our actual speed. They found that changes in visual flow and biomechanical activity led to changes in participants' calibration of walking distance, demonstrating the adaptability of human perception and action in varying conditions. Rieser et al.'s findings on perceptual-motor calibration raised interesting questions, particularly about how visual flow in virtual environments could influence the recalibration of distance perception.

Mohler et al. [38] extended these investigations into virtual environments (virtual big screen). In their study, participants were exposed to environments with artificially changed visual flow speeds while walking on a treadmill. Specifically, walking at twice the normal visual speed led to an underestimation of real-world distances by approximately 6%, whereas walking at half the speed resulted in overestimations of up to 11%. Additionally, they have found that participants overestimate in the visually matched condition by 3% due to two main reasons. One is due to the compression of distances in the virtual hallway during adaptation, and the second one is due to differences between walking on a treadmill and the ground, providing conflicting cues about self-motion.

Past studies by Mohler et al. [38] and Rieser et al. [46] revealed that people recalibrate their walking in response to altered visual conditions during locomotion. In both studies, participants walked with slower or faster visual flow than their actual biomechanical speed. My dissertation research extends these approaches by manipulating PEBW durations and analyzing the effects on distance judgments made in VR. The absence of vision during PEBW simulates the slower visual speed (a visually slower condition in Rieser et al.. [46] and Mohler et al [38]) condition from prior works, creating a mismatch between physical and visual movements. Additionally, this work examines eyes-open walking prior to PEBW to study if eyes-open walking can have a similar impact of PEBW on distance judgment results and also, using video see-through mode of the VR HMD provides an experience comparable to normal (matched) visual speed. My dissertation clarifies the relationship between prior locomotor experience and distance estimation in virtual environments by changing and varying pre-experiment walking durations.

## 2.6 Research Questions Addressed by this Work

This comprehensive study analyzes past and current experiments on PEBW and its implications for distance judgment. Subsequent chapters aim to answer key questions, such as the effects of different durations and types of PEBW on distance judgment. We discuss the methodology, procedures, and results obtained, analyzing the data and highlighting observations and conclusions. We consider patterns identified and how findings have expanded our understanding of PEBW's impacts on distance judgment in virtual environments. Then, discuss our recent experimental works utilizing the Oculus Quest-Pro to investigate new factors of PEBW that can impact distance judgment results. A recent experiment examined the impact of an extreme PEBW duration on distance perception, aiming to determine if a critical threshold could affect distance judgment differently and cause overestimation. Previous studies overlooked the impact of PEBW absence on distance judgment in direct blind walking. This research addresses this gap by systematically varying PEBW duration under consistent experimental conditions to evaluate its influence on distance judgment accuracy.

While prior works provide valuable insights into distance perception in VR, open questions remain regarding the precise connections between PEBW and distance judgment in VR. It remains unclear if certain PEBW durations reliably alter distance estimates. Additionally, it remains uncertain whether advanced headset features like see-through mode significantly impact distance judgment results. This work addresses these unresolved questions by manipulating PEBW durations across experiments and utilizing different VR hardware. The study explores how extending PEBW durations and introducing a see-through mode may influence distance judgments. By tackling these open questions, this work provides a good understanding of PEBW dynamics and its effects on distance perception in virtual environments.

# Chapter 3

# Experiment 1: Does Distance Walked in PEBW Impact Distance Judgments

This chapter builds upon work previously published at the Symposium on Applied Perception (SAP) [48], which also constituted a significant part of the Research Qualifying Exam (RQE).

## 3.1 Research Questions and Hypotheses

One key question that has not been fully explored in VR research is: How does the duration of PEBW affect how participants respond in a VR environment? This question is crucial for understanding the impact of PEBW on distance judgments. It also opens the door to answering other questions, such as how different durations of PEBW affect human sensory-motor responses in VR settings.

Our main hypothesis is that with more practice in PEBW, participants will become more confident and less cautious during blindfolded walks. We expect greater PEBW to lead to less underestimation of distances measured with direct blind walking. Similar to Philbeck et al. [40], we will also examine how distance judgment performance changes over trials. We expect to see larger changes between the beginning and the end of the experiment when shorter durations of PEBW are used. In addition, we will also record how long it takes participants to complete each trial to get a rough estimate of how participant confidence and walking speed might change over trials. The data collection strategy has been designed specifically to address these points. Data collection beyond simply recording the participants' walked distances is not unique to our study, but it is relatively uncommon.

Our study is designed with four different conditions where the amount of PEBW is varied. Participants performed PEBW by walking in a loop that was composed of

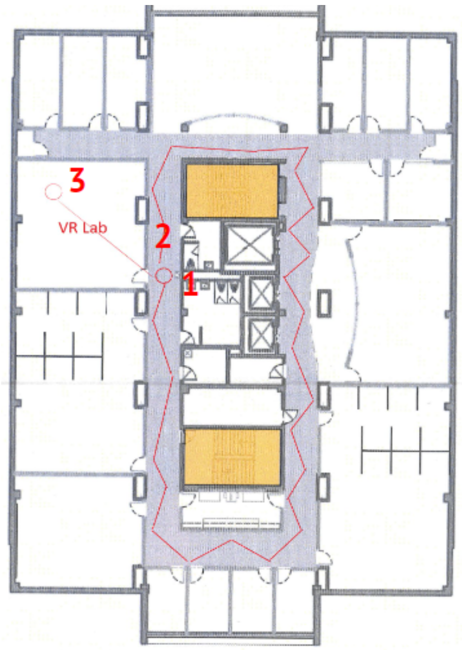


**Figure 3.1:** Illustration of a typical zig-zag path followed by a participant for one loop. Participants walked the loop in a counter-clockwise direction.

four hallways (shaped as a rectangle when viewed from above). We varied the number of PEBW "loops" that participants completed.

### 3.1.1 Experimental Design and Methods

The experimental design incorporated four conditions of PEBW: 0-loops, 1-loop, 2-loops, and 4-loops. A map of the hallway and a depiction of what a single PEBW loop path might look like is shown in Figure 3.1 and photographs of the four hallways that form a loop are shown in Figure 3.2. For studies that report the amount of PEBW they do, the most common durations are several minutes or 5 minutes (see Table 2.1). The durations of our 1-loop and 2-loop conditions are roughly consistent with

**Figure 3.2:** Photos of the four hallways which form the loop used for PEBW.

the typical PEBW durations reported in previous studies. The 0-loops and 4-loops conditions were therefore included to examine how increasing or decreasing PEBW compared to what is typical might impact results. The 0-loops condition also serves as a reference for what results you might expect when studies neglect to perform PEBW prior to the experiment.

Each condition involved a distinct duration of PEBW, represented by the number of

**Figure 3.3:** Oculus CV1 with Vicon tracker markers

loops completed while blindfolded in a rectangular hallway. For the virtual environment, we employed the Oculus CV1 Head-Mounted Display (HMD), as depicted in Figure 3.3. The VR rendering was performed using OpenGL technology (Figure 3.4). For the tracking system we have used 12 Vicon camera system setup in our lab.

Our virtual simulated room in the VR was one of the Computer Science Department's lab located in the Rekhi building. To enhance the realism of the virtual environment, various elements from the original lab, including furniture and decor, were integrated into the VR simulation. The objective was to create an immersive experience that closely aligns with the real-world setting.

The experiment was conducted in the VR lab situated on the fifth floor of the EERC Building. The lab's dimensions are approximately 8 × 7 meters, as illustrated in Figure 3.5. To maximize available walking distance, participants walked diagonally

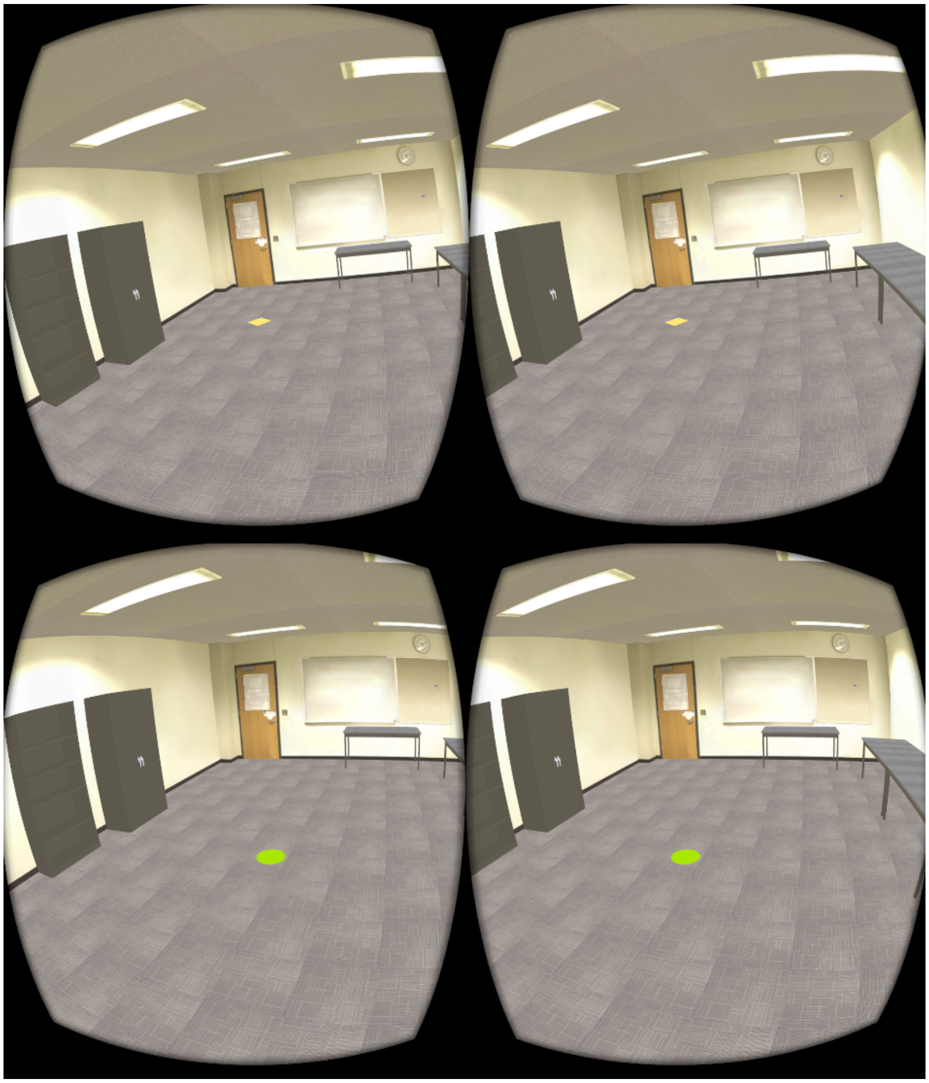

**Figure 3.4:** Virtual environment with a target at five (top) and three meters (bottom). The left and right side show the views generated for each eye for the Oculus CV1.

through the rectangular-shaped lab during the study. The headset was outfitted with infrared-reflective markers to enable precise tracking. The system's built-in orientation sensor complemented the tracking, ensuring smooth and low-latency orientation capture. We calibrated the tracking system prior to the first participant to ensure consistent and reliable performance over the experiments.

**Figure 3.5:** Virtual reality laboratory with Vicon tracking system.

### 3.1.2 Procedure: Pre-experiment blind walking

The study commenced with the participants signing consent forms. Subsequently, to ensure their ability to perceive depth using VR correctly, participants were required to view a random-dot stereogram through stereoscope glasses. Because some eyeglasses do not fit easily in the Oculus CV1, we recruited participants who did not need glasses for normal vision. Use of contact lenses was permitted. An eye chart was used to verify that all participants possessed 20/20 visual acuity.

To help ensure participants understood the instructions, the experimenter provided


**Figure 3.6:** Blindfold participants wore during PEBW.

both written instructions and verbal explanations. During the blind walking segment of the experiment, participants were explicitly instructed not to count steps or perform mental calculations. When their eyes were closed, they were instructed to visualize the virtual room and walk toward the targets and to stop walking when they thought they were standing on top of the target. These instructions were provided in the hallway outside the lab to prevent premature exposure to the actual VR laboratory setting (Figure 3.2).

Participants were assigned to one of four conditions, differentiated by the amount of PEBW performed. Each PEBW 'loop' refers to one complete circuit around a rectangular hallway path, and the conditions were defined as 0-loops, 1-loop, 2-loops, and 4-loops using a blindfold (Figure 3.6).

The hallways forming the loop were 2.5 meters wide. The full loop length, assuming participants walked perfectly straight, was approximately 73 meters. An illustration of what a typical path looks like is shown in (Figure 3.1). In the PEBW task, participants wore blindfolds, and then the experimenter asked them to start walking blindfolded. Since participants are blindfolded and do not see what is in front of them, they might drift to the left and right in the hallway. The path resembles a zig-zag for several reasons. First, the experimenter cannot perfectly point participants down the hall. Second, participants tend to drift and eventually reach a wall and must be safely stopped and turned. Lastly, once participants are stopped near a wall, they are simply turned in-place to face a safe walking direction (i.e., they are not brought to the center of the hall and pointed straight). Whenever participants were on the verge of colliding with a wall, the experimenter verbally notified them and turned them by their shoulders toward a safe walking direction.

After completing the assigned number of PEBW loops, participants, with their eyes still closed, were guided from the hallway to the experiment starting point in the VR laboratory (a distance of less than 10 meters). This means that participants in the 0-loops condition did experience a very limited amount of blind walking prior to the distance judgment trials. Ideally, we would have preferred to have no PEBW for the 0-loops condition. However, we wanted to avoid letting participants see the lab since previous work shows that seeing the real space can impact distance judgments [15].

### 3.1.3 Procedure: Direct Blind Walking Distance Judgment Trails

After completing the PEBW and guiding participants into the laboratory blindfolded, participants closed their eyes, removed their blindfold, and were assisted in donning the HMD. The experimenter helped the participant adjust the HMD, so it was comfortable. The participants opened their eyes and could see a blank screen. Once the participants indicated that the HMD was properly adjusted, the virtual environment was displayed, showing a virtual room and a virtual target on the ground (Figure 3.4). Participants were free to observe the virtual environment and target for as long as they desired. To mask any external sounds that could act as environmental landmarks, white noise was played until all direct blind walking trials were completed.

Participants were explicitly instructed not to count steps or memorize target distances to ensure the reliability of distance judgments. Once participants verbally indicated that they were ready to proceed, the experimenter blanked the screen, and they began walking toward the target with their eyes closed. When they believed they were standing on the target, they stopped walking and verbally confirmed that they were done walking by saying the word "stop." We electronically recorded the distance walked using the tracking system and noted the time. Next, participants were guided back to the starting location in the lab. When they returned to the starting location, the screen was unblanked, and participants were told to open their eyes. Then, participants would see the target for the next trial.

No feedback was provided during the trials. Participants initially performed two practice trials at random distances of 3.5 meters and 4.5 meters, although they were not informed these were practice trials. The main experiment consisted of 12 trials with target distances at 2, 3, 4, and 5 meters, presented in random order. To make it more difficult for participants to memorize or notice that targets appeared at the same distance multiple times, we also included three additional trials at distances of 2.5, 3.5, and 4.5 meters, making a total of 17 trials. Target shapes varied in width between 20 to 35 cm and took different forms, such as triangles, crosses, and squares. The targets also had different colors.

**Figure 3.7:** Clicker controller that was used during the experiment

To aid in blanking/unblanking the screen, advancing to the next trial, and recording the distance walked, , we employed a handheld presentation remote (Figure 3.7). This remote, often used in presentations, was chosen due to its easy one-hand operation, facilitating the experimenter in managing the experimental sequence while assisting the participant in navigating the VR environment. This approach helps the experimenter to run the experiment and, at the same time, control each step of the program.

### 3.1.4 Post-Experiment Procedures

Upon the completion of the experiment, participants were asked to complete a post-experiment questionnaire. In this questionnaire, participants were asked about their strategy, feelings during the experiment, and experiences with Virtual Reality (VR) in everyday life. To exclude data from our final analysis, participants who reported employing a strategy beyond mental visualization or imaging, such as counting floor tiles or steps, were excluded from the study. In order to ensure the reliability of our data, we also asked participants about any unexpected issues they encountered during the experiment.

## 3.2 Results

After implementing the exclusion criteria, a total of 72 participants (16 female) completed the study. 18 participants equally represented each condition. The age of the participants ranged from 18 to 35 years, with an average age of 22.5. All participants had a visual acuity of 20/20, and none of them wore eyeglasses, although some wore

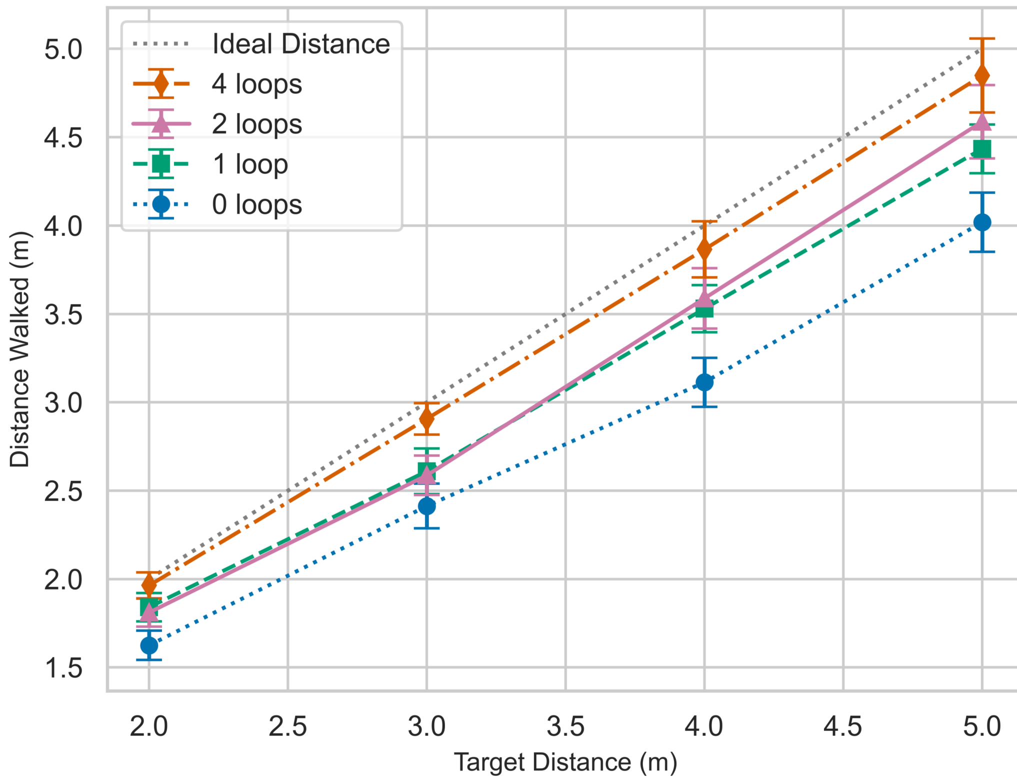


**Figure 3.8:** Distance judgment results. Error bars represent ±1 SEM.

contact lenses. A post-experiment survey revealed that 26% of participants had no prior VR experience. The results of are depicted in absolute terms (Figure 3.8) and as a relative percentage to the target distance (Figure 3.9). On average, participants walked 79.9%, 89.0%, 89.6%, and 97.2% of the actual target distance in the 0, 1, 2, and 4 loop conditions, respectively.

A mixed ANOVA was conducted on the walked distance data with target distance and condition factors. The results revealed that the number of PEBW loops significantly impacted the distance judgment trials ($F(3, 68) = 6.357, p < 0.001, \eta^2 = 0.219$). Additionally, as we expected, there was also a highly significant main effect of target distance on walked distance ($F(3, 204) = 1647.22, p < 0.001, \eta^2 = 0.960$), indicating

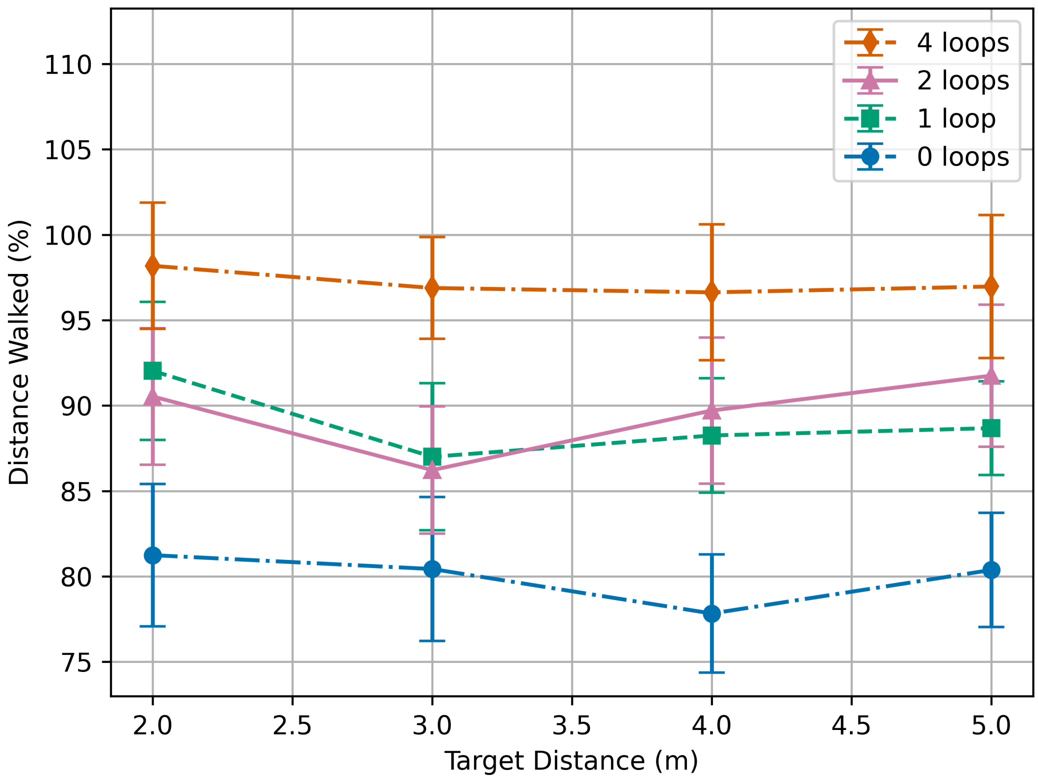


**Figure 3.9:** Distance judgment results as a percentage-based graph. Error bars represent ±1 SEM.

differences in walked distance across various target distances. Notably, there was a significant interaction between target distances and conditions ($F(9, 204) = 3.51, p < 0.001, \eta^2 = 0.135$) suggesting that the influence of target distance on walked distance varies depending on the specific condition, as evident from the slight deviations from linearity in the lines in Figure 3.8.

In a post hoc analysis, pairwise $t$-tests with Bonferroni correction were conducted following a repeated measures ANOVA to compare the different conditions. Among these comparisons, there were notable differences between most conditions. Specifically, conditions with 0 loops and 1 loop were statistically different ($p < 0.05$). Conditions with 0 loops showed significant differences when compared to 2 loops ($p < 0.05$) and when compared to 4 loops ($p < 0.001$). The comparison between 1 loop and 4 loops also indicated a significant difference ($p < 0.05$). However, the differences between 1 loop and 2 loops, as well as 2 loops and 4 loops, were not statistically significant.

Based on post hoc Tukey's tests for comparing similar target distances across different conditions, significant differences were generally observed between the conditions of 4 loops and other conditions (0 loops, 1 loop) across almost all target distances (2, 3, 4, 5) meters ($p < 0.05$). At the 2-meter distance, the difference between 4 loops and 2 loops was marginally significant ($p = 0.0422$). At the 3-meter distance, significant differences were observed between 4 loops and both 1 loop and 2 loops conditions. For the 4-meter distance, while the differences between 4 loops and the 0, 1 loop conditions remained significant, there were no significant differences between 4 loops and 2 loops. Similarly, at the 5-meter target distance, significant differences were noted between the 4 loops and the 0 loops and 1 loop conditions, but again, no significant differences were observed between 4 loops and 2 loops. Throughout these distances, no significant differences were detected between the 1 loop and 2 loops conditions.

Additionally, post hoc Tukey's tests for the variable target distances within each level

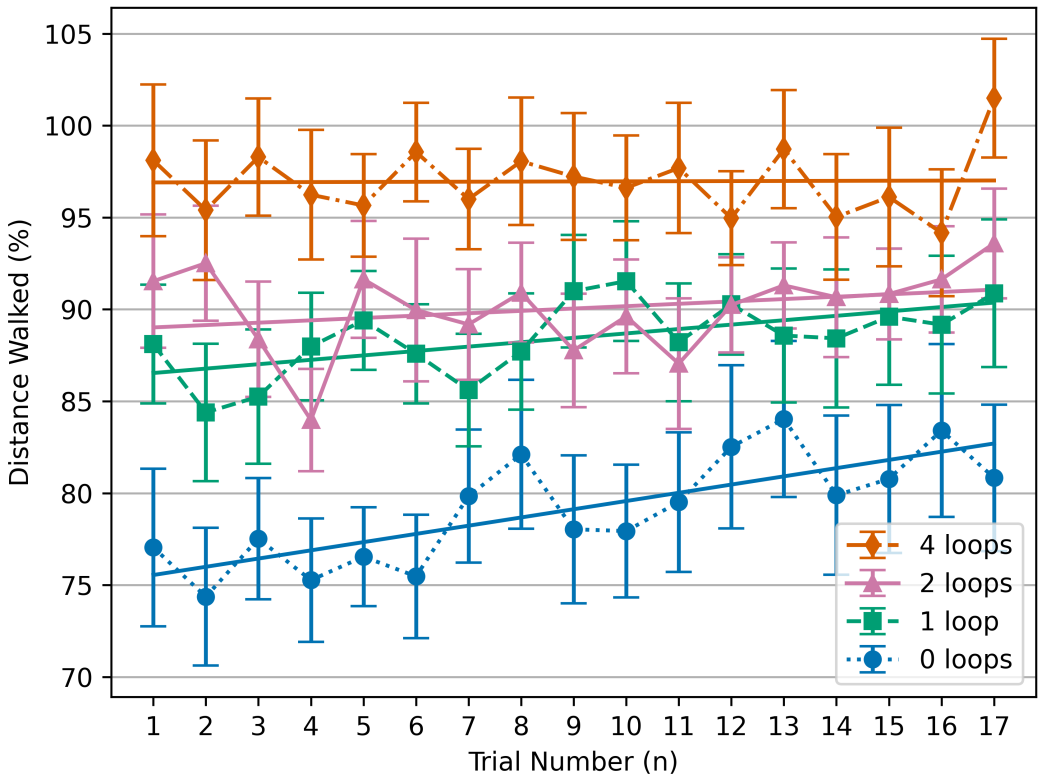


**Figure 3.10:** Averaged walked Distance over trials. Error bars represent ±1 SEM.

of condition, all pairwise comparisons for the differences in the walked distance across different target distances (2, 3, 4 and 5) meters within each condition (0 loops, 1 loop, 2 loops and 4 loops) were found to be statistically significant with p-values of less than 0.001. In other words, within each condition, the walked distance differs significantly across all target distances examined.

To examine whether participant performance evolved over trials, the percentage of distance judgment was plotted across all trials, as shown in Figure 3.10. The two practice trials and three additional trials aimed at making memorization more challenging were included in this graph but were not used in the previous analysis. The

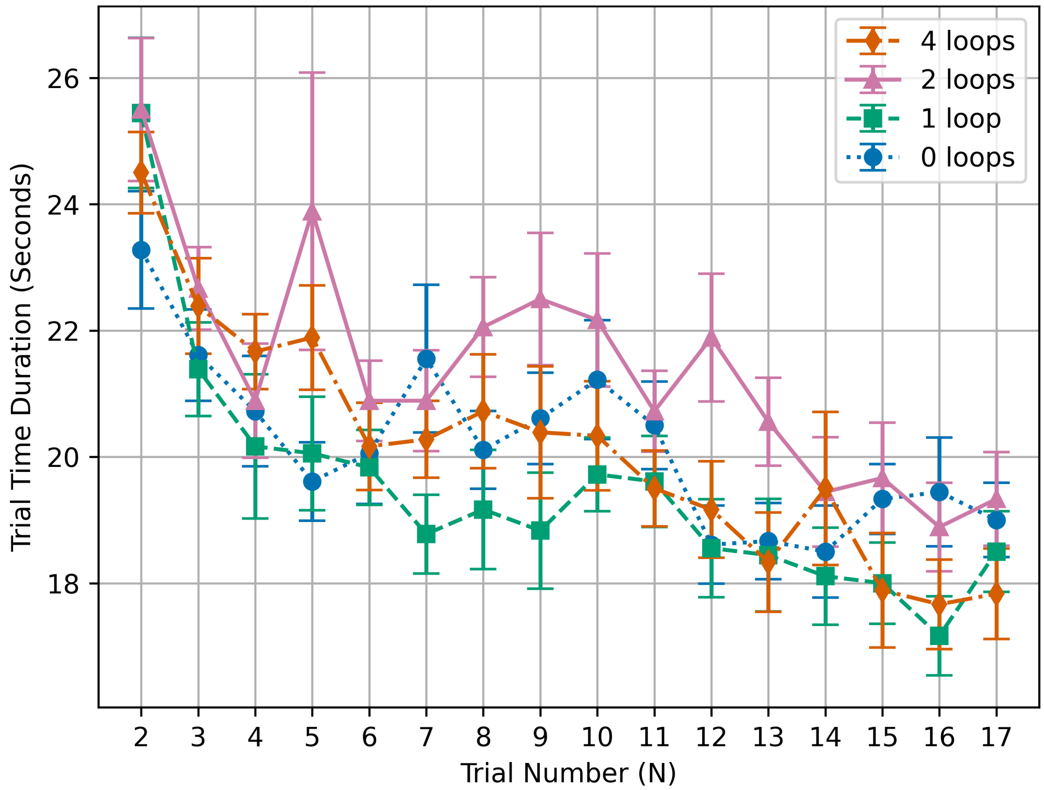


**Figure 3.11:** Duration measured from the end of each trial to the end of the direct blind walk in the subsequent trial. The first trial is excluded due to the methodology of data capturing. Error bars represent ±1 SEM.

results imply that an increase in the amount of PEBW results in less variation across trials during the experiment. Coefficient of determination ($R^2$) values were 0.60, 0.36, 0.08, and $< 0.01$ for the 0, 1, 2, and 4 loop conditions, respectively.

As previously discussed, we captured timestamps to measure the duration of each trial. Trial duration in this figure includes 3 parts: guiding participants back to the starting point, the time they spent looking at the virtual target, and the time they took for the direct blind walk for the direct blind task. Since data was recorded at the end of each direct blind walk, this prevented us from capturing the duration of the first trial. That is the reason 3.11 starts at trial 2.

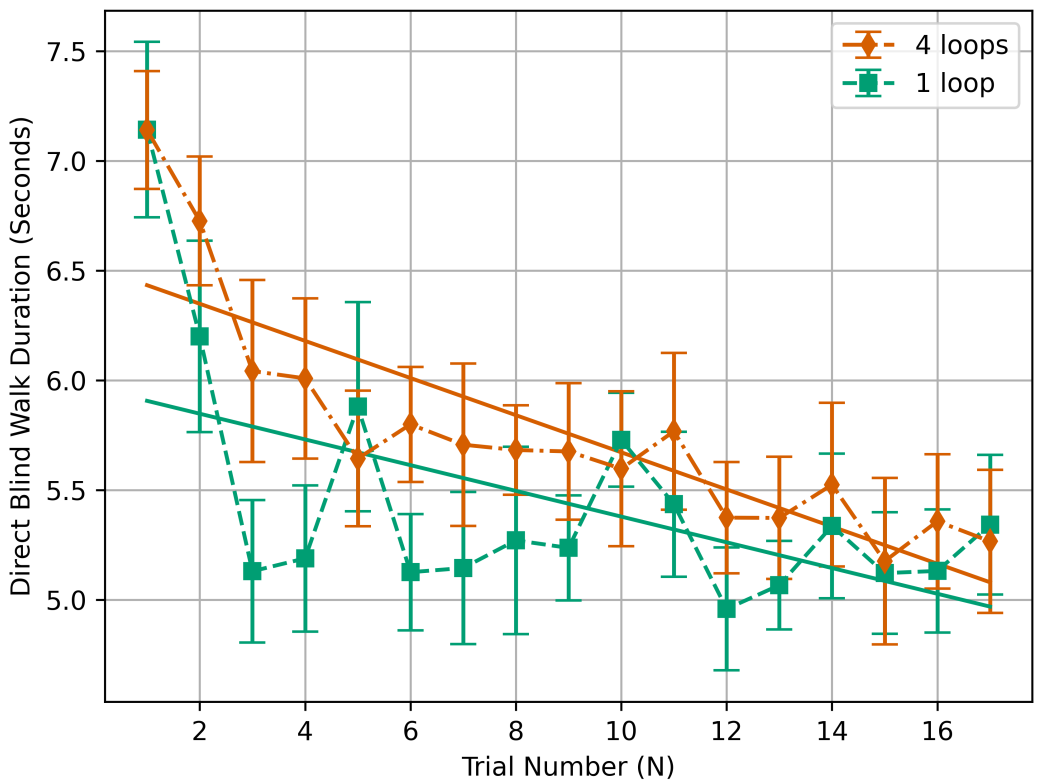


**Figure 3.12:** Duration of the direct blind walk during each trial. Error bars represent ±1 SEM.

The data shows a pattern of shorter trial durations as the experiment progresses over the trial. This trend could be due to participants becoming more comfortable with the tasks and possibly walking faster. After collecting data for the 0 and 2-loop conditions, we recognized that by recording the time when we blank the screen prior to the participants walking, we could more precisely measure the time it takes for participants to walk to the target. This extra information was collected in the 1 and 4 loop conditions. Figure 3.12 presents the duration data for the 1-loop and 4-loops conditions.

## 3.3 Discussion

This study establishes for the first time that PEBW has a significant impact on direct blind walking performance. More extensive direct blind walking yields consistent results over multiple trials. This adaptation is not dependent on feedback. Despite prior research [10, 11, 40] indicating that such an adaptation is possible, little attention has been paid to how PEBW procedures might influence experimental results. In order to conduct reliable cross-study comparisons, rigorous documentation and publication of PEBW procedures is essential. Our results suggest that, in order to compare two different VR distance judgment studies using the popular direct blind walking measure, one must recognize that different PEBW durations can cause a change in the experiment results.

Philbeck's study [40] discusses how blind walking without visual feedback influences direct blind walking distance judgments due to several factors, including perceptual-motor adaptation, increased familiarity and confidence, changes in strategy, and order effects relating to adaptation. Furthermore, Mohler et al. [37] conducted research on the impact of visual speed in a virtual environment on the calibration of real-world locomotion. The results demonstrated that participants tend to overestimate and subsequently overshoot distances after being exposed to slower visual speeds in the virtual environment.

In our view, two primary categories of explanations exist. One primary explanation for the observed outcomes related to participants' adjustment to the lack of visual feedback during PEBW practice. Typically, visual cues play a crucial role in distance estimation and speed during walking. However, these cues are absent in PEBW due to a lack of visual feedback. The brain expects to receive visual input to estimate distance and speed but gets none, leading participants to feel like they haven't walked far enough when later asked to walk to a target blindfolded. This experience aligns with findings from other studies where visual speed is artificially slowed, causing participants to overestimate distance [38, 46]. The absence of visual feedback in PEBW could result in this kind of sensory mismatch. In other words, walking without visual feedback during PEBW may feel like you are moving slowly because you do not receive visual input indicating that you are moving. Then, subsequent attempts to walk to a target while blindfolded may lead you to walk further than you would have without PEBW. On the other side, for the 0 loops condition, since there was no PEBW, participants were expected to walk at their normal pace despite the mismatch between visual inputs and blind walking velocity. Even though participants are walking blindfolded at a slower pace, they mentally project their normal eyes-open walking speed, which makes them imagine getting closer to the targets faster, leading them to stop prematurely and walk shorter distances in addition to fear and anxiety of walking blindfolded.

The second category of explanations involves cognitive factors, specifically participants' trust in the experimenter and their level of comfort and confidence while walking blindfolded. Without adequate PEBW practice, participants might be hesitant to walk freely due to the fear of colliding with real-world objects. This fear could be caused by not being able to see the unknown real-world environment in front of them when they are wearing VR HMD and are blindfolded. As participants complete more trials or perform additional PEBW, they become increasingly comfortable and confident, likely reducing anxiety and the fear of collision. For example, we suspect that the increased time needed to walk to targets in the first few trials (Figure 3.12) is likely due to both unfamiliarity with the task and lack of confidence walking in the first trials after wearing the HMD. This acquired comfort could be another reason we observed changes in walking behavior and distance estimations over the experiment.

## 3.4 Limitations and Challenges

In our study, we noticed a variety of behaviors among participants during the PEBW practice sessions. Some were noticeably cautious, walking at a slower pace and appearing hesitant. Others moved more quickly but had difficulty maintaining a straight path, requiring frequent interventions to prevent collisions with walls. These observations grabbed our interest in exploring these behavioral differences more deeply. However, some limitations constrained this aspect of our investigation. Our current equipment setup did not allow us to capture detailed data on participants' walking behaviors, such as their velocity, their walking patterns, or the number of times they turned during PEBW. This lack of data is a limitation because these unrecorded variables could provide invaluable insights. For instance, they could reveal how participants' confidence and walking strategies evolve during the PEBW practice and the actual trials. Further, by capturing this data, we could more accurately determine whether these behavioral variables correlate with changes in distance estimation. This would also let us analyze whether participants exhibit a consistent pattern of adaptation as they go through multiple trials.

In addition to these limitations, several areas require more focused research. One area is the influence of pre-experimental activities, such as how much walking participants did before taking part in the experiment. Might we expect that participants who walked a mile to get to the experiment have different results compared to someone who walked down the hallway to do the experiment? While our work shows that eyes blindfolded PEBW impacts distance judgments, it does not indicate if extensive eyes-open walking might impact them.

Another interesting area for future study is the potential impact of modern HMDs' video see-through features on participants' comfort and trust levels. This is particularly relevant given that many of our participants had not previously used a VR device or had little experience with it. The see-through feature allows participants to see video footage of the real world while wearing the device, which could help with anxiety and build trust in the technology. If participants can learn that they can trust the visuals that it is showing them during an eyes-open pre-experiment walk, perhaps this might increase trust when the virtual room and target are displayed leading to increased distance judgments. We can better understand the multiple factors influencing participants' performance and adaptability in similar experiments by investigating these aspects.

Furthermore, our study is limited in scope regarding the methods employed to measure distance judgment. We focused exclusively on direct blind walking due to its frequent application in similar research, as documented in our literature review (see Table 2.1). However, this focus leaves several other measurement methods unexplored. For example, we have not investigated whether the effects of PEBW extend to other distance judgment techniques like blind throwing or verbal reporting. However, it is also uncommon for PEBW to be used with these techniques as they do not require participants to walk blindfolded. Nonetheless, it remains an open question whether PEBW would influence them in the same way it impacts direct blind walking. Thus, the impact of PEBW on other distance judgment methods represents an avenue for future research that could provide a more comprehensive understanding of its effects.

Another aspect of our study that introduces limitations is the specific environment and equipment used for conducting PEBW. We conducted the PEBW sessions in a corridor that measures around 2.3 meters in width and approximately 73 meters in length. The dimensions and characteristics of this space could have influenced participants' walking behavior and distance estimations. It's worth noting that different spatial settings could potentially yield different results, raising questions about the generalizability of our findings to other environments. Similarly, the choice of VR headset used in our experiment, which was the Oculus CV1, presents its own set of limitations. Different headsets come with varying field-of-view, tracking accuracy, and visual fidelity, all of which could influence participants' perceptions and behaviors. Therefore, the use of a different VR headset in future studies may produce results that diverge from those we observed, adding another layer of complexity when interpreting and comparing findings

## 3.5 Conclusions and Future Work

Our research findings emphasize the importance of documenting and publishing PEBW procedures. If PEBW is minimal or absent, distance judgments in HMDs can be significantly compressed, resulting in more distance compression and underestimation. Philbeck's real-world study [40] suggests three minutes of blind walking. Our PEBW for the 1 loop and 2 loop conditions took about 3 to 5 minutes. The duration of these two conditions is similar to the typical duration indicated in the studies shown in Table 2.1.

We also found that longer periods of blind walking before the experiment can improve performance. If extensive amounts of PEBW were used beyond what we studied, it might produce results similar to our 4-loop condition, or it might result in distance overestimation. The right amount of time for this activity might vary depending on the specific goals of the study or application. Researchers will need to balance time spent on this against the benefits, especially since our most extensive PEBW setup is quite time-consuming. At minimum, it is critically important that researchers document and publish their PEBW procedures with their studies to help in the comparison of studies.

While our study presents valuable insights, several areas remain unexplored. For instance, the influence of prior VR experience on distance judgment remains uncertain. In upcoming research, we plan to explore the effect of modern VR features, like the 'see-through' mode offered in newer HMDs. This feature may help build participants' trust in the virtual environment, thus possibly improving distance judgments.

# Chapter 4

# Experiment 2: Exploring Different Types of PEBW

In the previous chapter, we conducted an initial study examining how the duration of PEBW affects distance judgments in virtual reality. While the results demonstrated a significant influence of increased pre-experiment walking on reducing distance underestimation, several questions emerged that needs further investigation. This next chapter details a follow-up study aiming to address limitations and unresolved questions raised by our preliminary research.

Specifically, we intend to collect more detailed behavioral data on factors like walking velocity, patterns, and turns during both pre-experiment walking and distance judgment trials. By leveraging the advanced tracking capabilities of the Meta Quest Pro headset, this experiment will provide insight into the potential relationships between adaptation processes, confidence, and distance estimation. We will also evaluate the effects of various pre-experiment walking modalities, including extensive blind walking and the use of see-through video.

The main goal is to deepen understanding of the complex connections between methodology, behavior, and distance perception. Through in-depth analysis of variables enabled by Quest Pro's real-time data collection, we can elucidate the mechanisms underlying the influence of pre-experiment walking on subsequent distance judgments observed previously. This chapter outlines the rationale, design, and results of our follow-up study.

## 4.1 Research Questions

Several open questions remain from our previous experiments on PEBW that this work aims to address. Differences were observed in how participants performed during PEBW, prompting inquiry into why these variations occurred and how they may influence results. Unique behaviors also emerged in participants' walking paths, number of turns taken during PEBW, and velocities during PEBW and blind walking that require further investigation. Upon reflection, we believe examining the relationship between PEBW walking velocity and distance judgment is important for a more thorough understanding. We hypothesize participants who lack confidence during PEBW

**Figure 4.1:** Meta Quest-Pro device with controllers

may display slower velocities, which could correlate with greater underestimation of distances. Similarly, we also hypothesize that participants with longer PEBW times walked further distances, raising the question of whether greater confidence and trust in blind walking from additional PEBW time impacted estimates. The potential effect of normal, eyes-open walking before the experiment also remains unclear and will be examined. Additionally, this work explores whether increased PEBW time improves participants' comfort levels and trust, potentially observable through changes in walking velocity. By investigating these unresolved issues, this research elucidates the intricate relationship between PEBW and distance perception in virtual reality.

In our initial study, the data collection was limited to basic metrics such as the distance participants walked each trial, and basic timing information about how long it took participants to complete a trial. Measuring the time from when the screen is blanked at the start of the trial until when a participant stops walking and believes that they are standing on the target is imprecise since participants may take an extra moment to think about their response. Further, the timing depends on the experimenter quickly and accurately pressing a button to record the time. This limited scope made it difficult to investigate the underlying reasons for distance underestimation in VR. For example, walking speed during pre-experiment walking, step size throughout pre-experiment procedures and distance trials, and walking speed are all additional variables we were curious about. To address this, we've revised our experimental design to collect continuous tracking data during pre-experiment procedures and the experiment itself. The purpose of this enhanced approach is to gain a more complete understanding of how distance perception operates in a virtual environment.

As previously discussed, an outstanding question remains regarding the potential impact of participants' walking before the experiment on their distance judgment abilities. Since PEBW is known to influence participants' distance estimates in VR, it is unclear whether this effect stems solely from blindfolded walking before the virtual environment exposure or if even regular eyes-open walking before the study could alter distance perception due to walking action itself (whether it is blindfolded walking or eyes-open walking). This is an essential factor to examine, as many participants naturally walk to the lab before participating in VR distance judgment experiments using direct blind walking. If normal walking before the study impacts results, it could significantly change perspectives on distance judgment in VR. Therefore, this work will analyze whether walking to the lab with vision intact affects participants' subsequent distance estimates in the virtual environment, helping clarify the boundaries of PEBW's effects.

In addition to real-world eyes-open walking prior to the experiment, a related topic can also be examined: Eyes open walking using a VR headset which displays the real world to the user using video see-through technology. Video see-through technology creates an augmented reality-like experience with a traditional non-see-through headset. It uses color cameras mounted on the outside of the headset to allow participants to see the real world while wearing the headset (and possibly augmented reality graphics superimposed on top). Although walking with a video see-through headset largely presents the same information to the user as real-world walking does, video see-through may allow participants to become more confident and have more trust in the headset. Since our research recruits subjects with varying levels of VR experience, many are unfamiliar with VR devices. This unfamiliarity could contribute to the underestimation of distances. We hypothesized that using the see-through mode to simulate real-world walking before the VR experiment may improve participants' ability to judge distances accurately by increasing their comfort and familiarity with

VR walking. We wondered if see-through pre-experiment walking might benefit distance judgments and how it would compare to the traditional PEBW procedures used in the previous chapter. Further, we wanted to compare how it performed to eyes-open real-world pre-experiment walking. Our study provides initial evidence on the influence of real walking viewed through VR headsets on subsequent distance estimation, elucidating the potential of see-through technologies to enhance spatial judgments.

Due to the advancement of VR HMDs, we also thought about other details that we can use to analyze our participants' behavior more closely, such as participants' walking velocity during the PEBW and direct blind walk, participants' walking patterns, turnings during PEBW, and step size. Related to walking steps behavior, Mohler et al. [35] investigated the effects of virtual reality on walking gait compared to real-world walking. Their study measured both the walking velocity and step size of participants, finding that those wearing a VR headset moved more slowly and took shorter steps than they did in real-world conditions. This suggests that using a VR headset alters one's natural gait, even when the eyes are open. We also plan to take a look at these types of details, such as walking steps during the direct blind walk, to determine participants' confidence and trust in using VR HMDs.

### 4.1.1 Experimental Design and Methods

In our experiment, we designed four different conditions to investigate PEBW. The first condition had just one loop of PEBW and served as our control condition. We chose one loop because its duration aligns well with previous studies and experiments done by other researchers. Our previous research also found that one loop and two loops yield similar results, and due to this reason, we preferred to use 1-loop of PEBW due to its shorter duration. In the second condition, participants walked eight loops with their eyes open and then completed one PEBW loop. This setup was to see how regular walking with eyes open might influence the performance in PEBW. For the third condition, participants made eight loops of PEBW to study exposure to an extreme amount of PEBW and see whether it could cause overestimation. The fourth and final condition involved eight loops of walking while using the see-through video mode on a VR headset.

† Pre-Experient Walking Task Type:

- 1 PEBW loop
- 8 Eyes-Open loops + 1 PEBW loop
- 8 PEBW loops
- 8 See-Through loops

### 4.1.2 Pre-experiment Procedure

Mirroring the protocols of our previous experiment, all participants were mandated to provide informed consent prior to their participation in this study. To ensure that participants were qualified for the tasks at hand, we instituted a series of preliminary evaluations, including a stereo blindness test and a visual acuity test. Our experiment permitted glasses as long as they fit under HMD. Contact lenses were also acceptable. All participants passed the visual acuity and stereo blindness test and had visual acuity of 20/20. Additionally, we measured participants' Inter-Pupillary Distance (IPD) using a dedicated smartphone application, allowing us to fine-tune the HMDs IPD range of the Meta Quest Pro devices for each participant. After these preliminary checks, participants were presented with instructions regarding the experiment.

This study worked on the advanced capabilities of the Meta Quest Pro device and relied heavily on its embedded tracking system. Before the onset of the experiment, we calibrated the VR device. The device's guardian feature, a safeguard designed to limit users from straying beyond a predefined boundary, was deactivated. This modification allowed participants to walk unrestricted during the VR pre-experiment and experiment sessions. In the condition involving eight loops of Eyes-Open walking preceding one loop of PEBW, participants set the HMD on their foreheads to enable data collection during their walk when they followed eyes-open walking before the PEBW task. Participants were instructed to maintain a normal walking pace throughout this condition. Upon completion, the HMD was positioned over the participants' eyes, with the screen left intentionally blank to prevent any real-world viewing for the PEBW task. We integrated side blockers with the Meta Quest Pro to entirely eliminate peripheral light during the PEBW phase. This decision was based on a study by Li et al. [27], which highlighted the significance of light simulation on peripheral vision under VR HMDs in influencing distance perception. Our aim was to ensure that such factors did not bias our results. Throughout the experiment, white noise was permanently played to isolate participants from auditory cues from the real world. Utilizing the special capabilities of the Quest Pro, we collected participant data at every frame (on average, 70 frames per second). In contrast, for the condition that did not involve prior eyes-open walking, participants were directly escorted to the designated hallway and then equipped with the headset at the starting point of the PEBW procedure and initiated the PEBW phase. The same protocol was followed for these participants, except for omitting the eyes-open walking phase. During the PEBW, the experimenter used the button on the Quest Pro controller to record instances where participants stopped and turned. This approach to data collection helps to provide a deep understanding of participants' navigation behaviors within the VR environment. Data we have collected during our experiment will allow for a more detailed understanding of the relationship between real-world walking experiences and distance perception in VR contexts.

Moreover, an identical experimental methodology was employed for those participants

**Figure 4.2:** Screenshot of see-through video captured via the Quest Pro in the hallway outside the laboratory.

assigned to the see-through mode conditions. In these circumstances, participants had the opportunity to view the hallway via the camera lenses incorporated within the Quest Pro, a visualization of which is provided in Figure 4.2. Initially, these participants were instructed to traverse eight continuous loops under the see-through mode at their normal walking pace. After the prior see-through walking of 8 loops, the screen was intentionally rendered blank by the research team, enabling the safe transition of the participants into the laboratory. A key distinction for participants in this condition was their lack of exposure to any blind walking prior to the experiment.

### 4.1.3 Experiment Procedure

After completing the PEBW task, participants were guided into our laboratory with the VR HMD securely fitted, but the screen was switched off. They were also instructed to keep their eyes closed during this transition. We found that transitioning from the bright hallway into the dark lab sometimes caused problems with the tracking system, where the virtual eye height was clearly wrong. Therefore, we performed a short calibration process once participants were in the laboratory. To perform the calibration, the experimenter gently removed the VR HMD from the participant's head and helped them put on a blindfold, ensuring they kept their eyes shut throughout this process. The participant waited approximately one minute while the experimenter recalibrated the device. Following calibration, participants were asked to remove the blindfold. Still keeping their eyes closed, they were aided in putting the VR HMD back on. We did not notice any other noticeable tracking system problems in the hallway or the lab during the study.

Participants were then instructed to open their eyes and view the virtual room. In alignment with the procedure of the previous experiment, participants were permitted to visually scan their surroundings from their initial position for an unlimited amount of time; however, they were not allowed to explore or move within the VR room physically. Once participants signaled readiness, data collection began with the target becoming visible, and the experiment continued as described in the prior chapter.

**Figure 4.3:** Virtual environment with a target at 3.5 meter using Meta Quest Pro

Although we did not notice any noticeable tracking issues during the direct blind walking trials, we performed one additional step to help ensure that the virtual targets were displayed accurately. In the previous study, we relied on a room-mounted tracking system that was known to have little amount of drift over time. In this study, we were concerned that any amount of drifting using the built-in HMD tracking system would interfere with our study. Specifically, even though we always bring participants

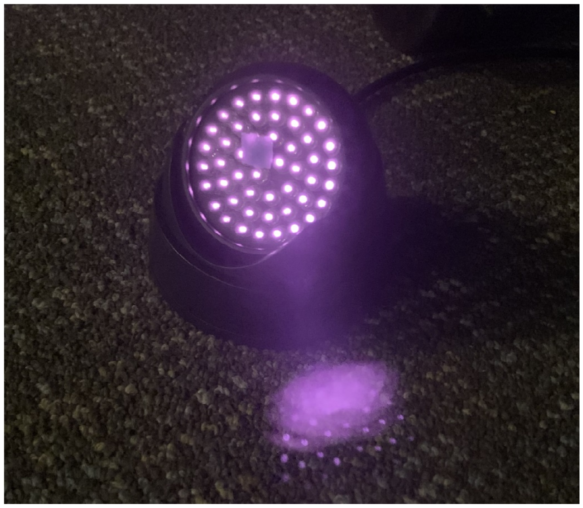

**Figure 4.4:** IR Light for VR during the experiment

back to the exact starting location (marked on the real floor with a piece of tape) and facing the correct direction, tracking system drift over time may cause the system to incorrectly calculate that the user is not at the intended starting position. Errors could cause the target to appear at the wrong distance or to be positioned in the wrong direction. We ensured that the virtual world was oriented such that the target always appeared directly ahead of the participants, positioned at the correct distance by resetting the position of the user in the VR world at the end of each trial before starting the next target when we have adjusted participants on the correct starting point in the real world. This level of control over participants' starting position and orientation between trials was not implemented in previous studies, but we used it as a precaution in this experiment to avoid any problems with the newer, built-in tracking technology in the HMD. We also used additional infrared lights in the lab to help the Meta Quest Pro's infrared cameras track its location more reliably in a dark room. We used two external infrared light sources (Figure 4.4) in the lab laboratory

(Figure 4.5). We found that the tracking worked more reliably in the dark lab with the lights.

One extra benefit of this additional step to ensure the starting location and direction towards the VR target was correct is that it also avoids any small errors resulting from the experimenter not accurately placing participants on the tape that was marked as the start location in the lab. For example, if the participant is placed a few centimeters too far behind the start location, in this experiment, the target location would also be moved a few centimeters closer so that it should be exactly the correct distance from the participant. Additionally, if the participant's head direction towards the previous objects was changed (since sometimes it's hard to adjust participants' head direction towards the previous target), the participant's head direction also reset by default in the VR room towards the VR targets. This ensures that they are facing the VR targets correctly and helps to avoid any issues related to direction. The previous experiment relied on the experimenter accurately placing participants at the start location.

### 4.1.4 Post-experiment Procedures

After the completion of the experiment, participants were requested to complete a post-experiment questionnaire. This helped us to quantify and ask some of the usual questions, such as participants' experiences with VR, or questions to make sure they

**Figure 4.5:** Laboratory set up for Experiment 2

did the experiment correctly, such as not counting their steps. to see if any issues happened during the experiment and how familiar participants were with VR.

## 4.2 Results and Discussion

In the following sections, we analyze the results of different aspects of the study and discuss them individually.

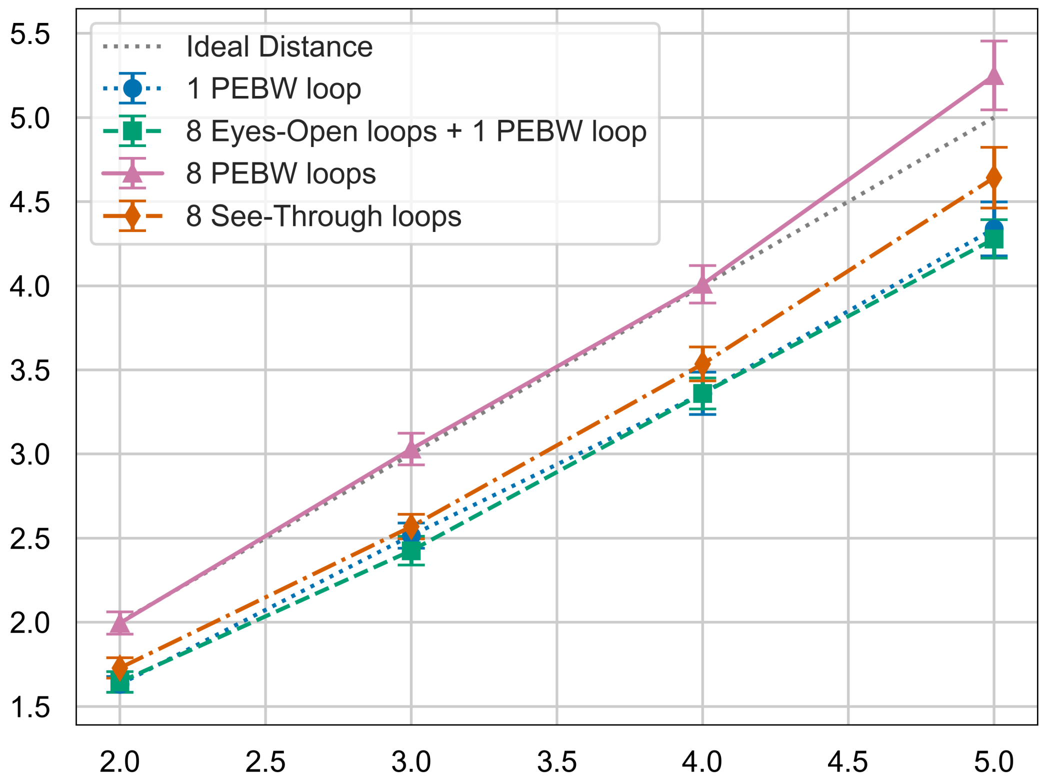


**Figure 4.6:** Distance judgment results. Error bars represent ±1 SEM.

### 4.2.1 Direct Blind Walking Distance Judgments

A total of 64 participants (25 of whom were female, 1 non-binary) successfully completed the study. Each condition was represented by 16 participants, with ages ranging from 18 to 35 years. All participants exhibited 20/20 visual acuity, and none had previously visited our laboratory. Contact lenses were allowed for the experiment, and eyeglasses were allowed as long as they fit under VR HMD on the Meta Quest-Pro. We had one participant who had eyeglasses and took a visual acuity test with her eyeglasses, and others took the visual acuity tests without any eyeglasses. A few

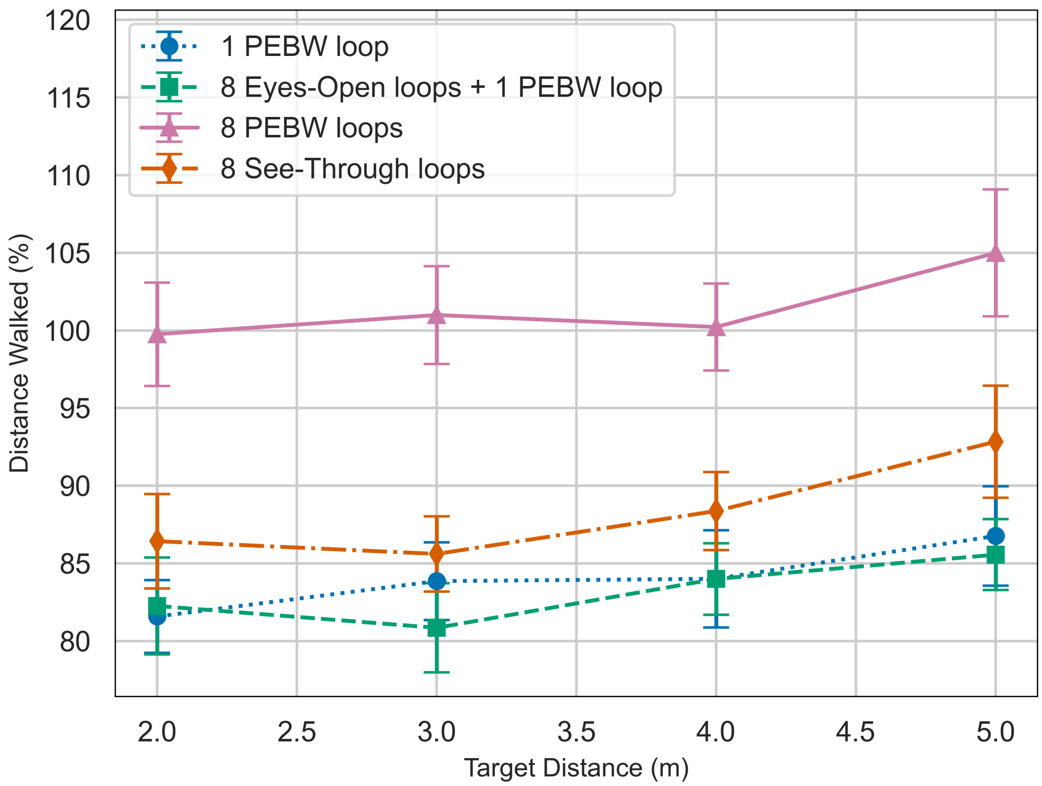


**Figure 4.7:** Distance judgment results as a percentage-based graph. Error bars represent ±1 SEM.

participants were necessarily excluded from our data set due to failing either the visual acuity or stereo-blindness tests, and we did not count them into the experiment. The mean age of our participants was 22 years. A post-experiment survey revealed that 20% of the participants had no prior experience with virtual reality. The resulting data from our experiment are visually represented in Figures 4.6 and 4.7. On average, participants walked 84.62%, 83.64%, 102.02% and 89.10% for 1 PEBW loop, 8 Eyes-Open loops + 1 PEBW loop, 8 PEBW loops and 8 loops See-Through loops conditions respectively.

In our analysis using Mixed Repeated Measures ANOVA, we found meaningful differences in walked distance based on target distance and condition. Specifically, the type of condition had a notable impact on the walked distance, $F(3, 60) = 10.05, p < 0.001$, and this was confirmed by a large effect size ($\eta^2 = 0.334$). As we expected, the target distance showed a strong impact, $F(3, 180) = 1189.438, p < 0.001$, supported by an extremely large effect size ($\eta^2 = 0.952$). Additionally, the interaction between target distance and condition also significantly affected the walked distance, $F(9, 180) = 2.727, p < 0.01$, with a moderate effect size ($\eta^2 = 0.119$).

In a post hoc analysis, pairwise $t$-tests with Bonferroni correction were conducted following a repeated measures ANOVA to compare the different conditions. The main result shows that the 8 PEBW loops condition was significantly different than each of the other conditions (all comparisons had $p < 0.01$). All combinations of the other three conditions (1 PEBW loop, 8 Eyes-Open loops + 1 PEBW loop, and 8 see-through loops) were found not to be statistically different from each other $p > 0.05$. Therefore, although the 8 see-through loops condition appears to perhaps result in slightly higher distance judgments than the 1 PEBW loop as shown in (Figure 4.7), this difference is not statistically significant than our control condition (1 PEBW loop).

Additionally, post hoc Tukey's tests for the variable target distances within each level of condition revealed that all pairwise comparisons for the differences in Walked Distance across different target distances (2, 3, 4, and 5 meters) within each condition

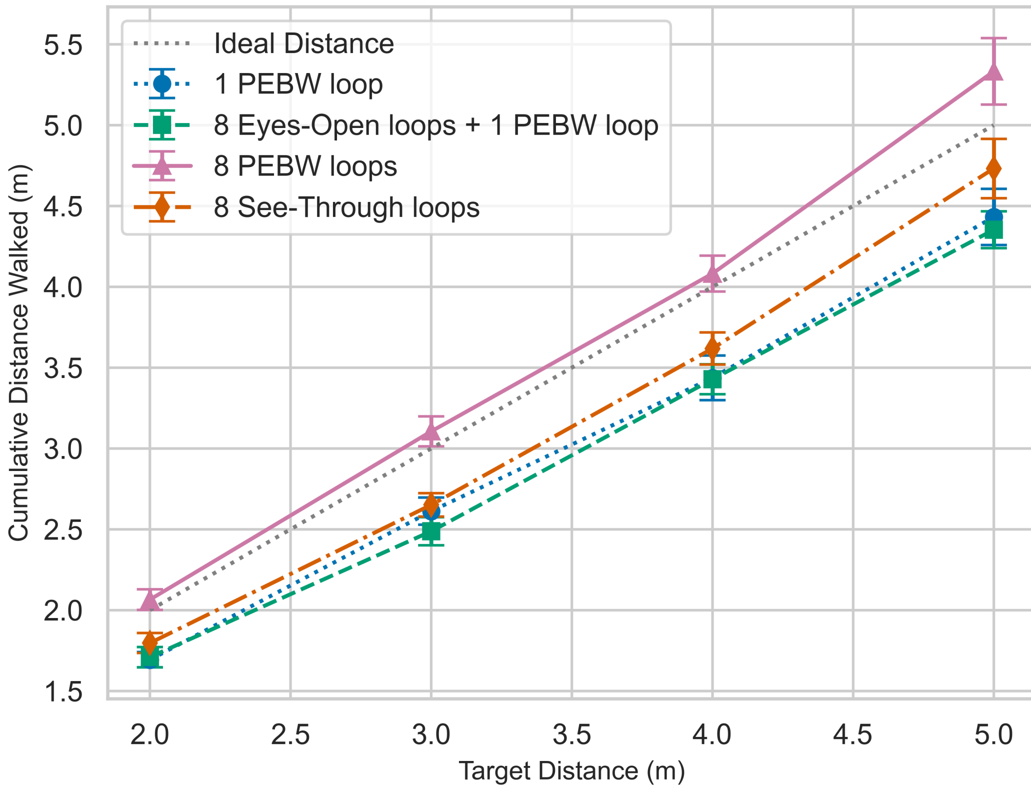


**Figure 4.8:** Cumulative Distance judgment results. Error bars represent ±1 SEM.

(1 PEBW loop, 8 Eyes-Open loops + 1 PEBW loop, 8 PEBW loops, and 8 See-Through loops) were found to be statistically significant with $p$-values of less than 0.001. In other words, the walked distance differs significantly within each condition across all target distances examined.

In the results presented in the previous chapter and the results above, we calculated the distance walked as the Euclidean distance from the participant's starting location and their stopping location. However, since we continuously recorded the participant's positions in this experiment, we can also calculate the distance walked as the sum of the distances between consecutive frames. These distances are typically not

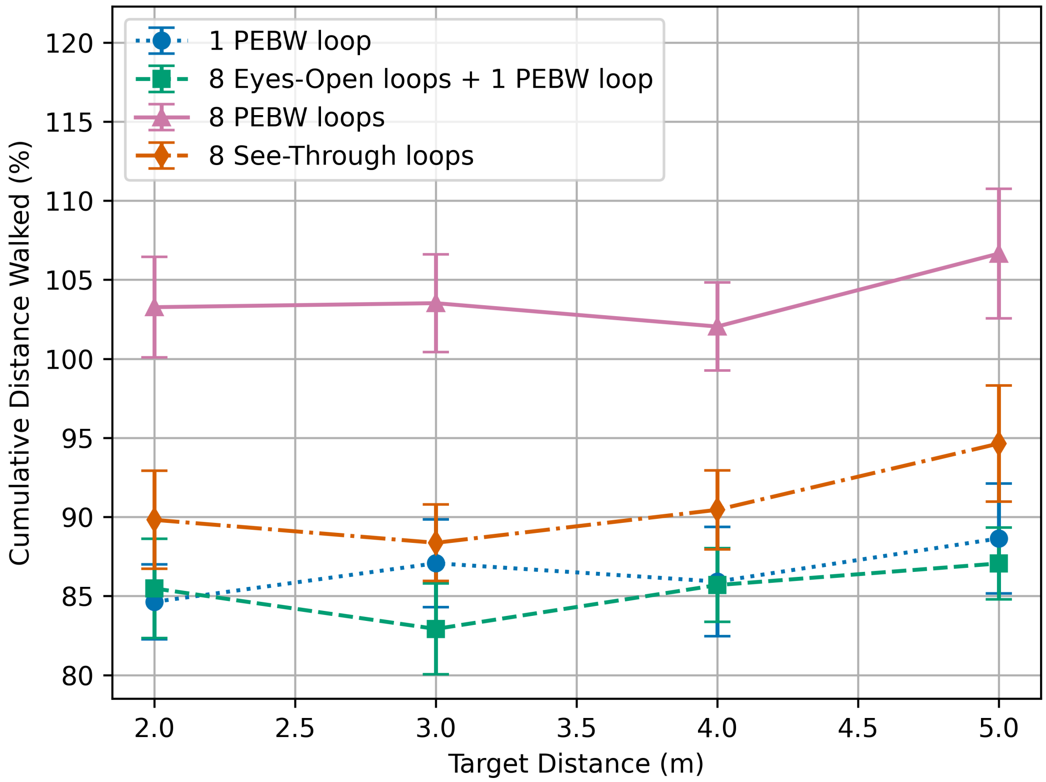


**Figure 4.9:** Cumulative Distance judgment results as a percentage-based graph. Error bars represent ±1 SEM.

possible to record in real world experiments. They also are necessarily longer than the previously reported distances since participants do not walk in an exact straight path. Our aim was to capture any deviations and fluctuations in walking distance that might occur during the participants' direct blind walk. These extra calculations give us a closer look at how the participants walked, showing details we might miss by only looking at the start and end points. You can see this data in Figures 4.8 and 4.9. We will talk about this and how we calculated the cumulative perceived distance in Chapter 5

Similar to the previous experiment, we also calculated how performance changed over

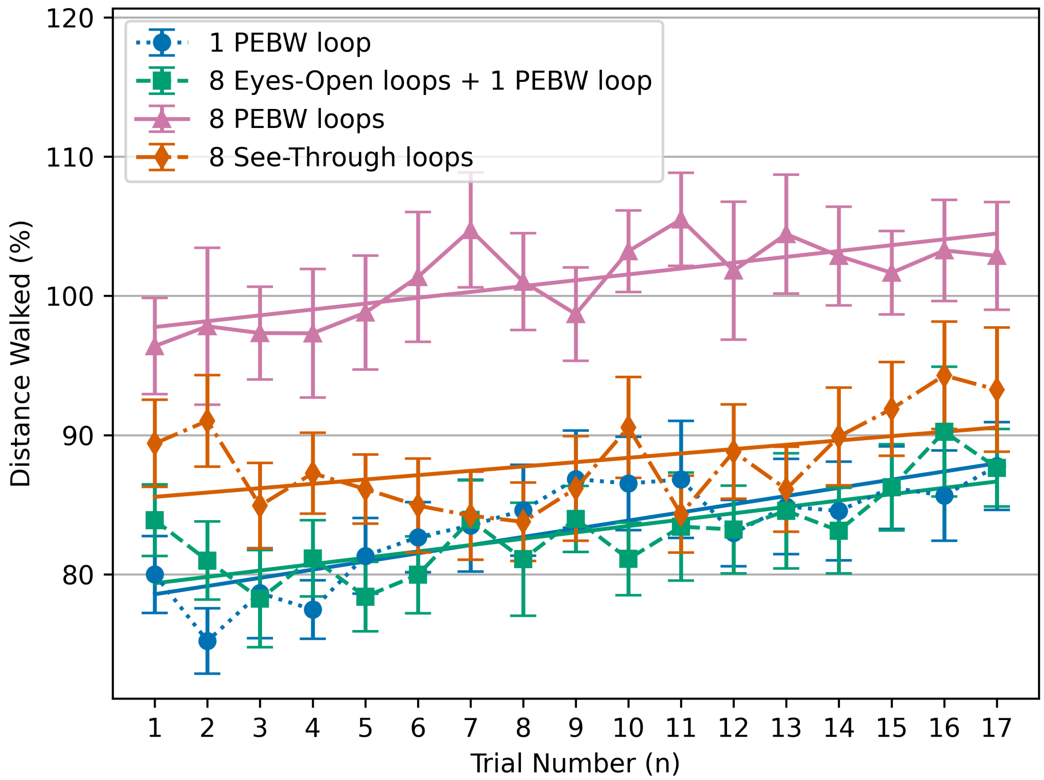


**Figure 4.10:** Averaged walked Distance over trials. Error bars represent ±1 SEM.

trials (Figure 4.10). This graph illustrates the average distance estimations by participants in each condition over 17 trials. We observed that participants adjusted their responses, perceiving longer distances as the trials continued. This trend aligns with findings from Chapter 3. However, when participants underwent 8 PEBW loops, their adaptation was notably more pronounced. Unlike our initial assumptions based on earlier chapters, after experiencing four loops, the responses did not remain consistent. Instead, we found that participants tended to overestimate their perceived distance following intensive adaptation.

Building on the findings from Chapter 3, where we demonstrated that four loops of PEBW significantly influenced the participants' ability to judge distance with an overall accuracy exceeding 97%, we were intrigued to explore the effect of an extreme PEBW exposure, specifically eight loops, on distance perception. The 8 PEBW loops condition represents a situation where a participant performs an extensive amount of pre-experiment blind walking that is far longer than most experimenters would consider doing because it took approximately 16 minutes to complete. This study shows that doing this excessive amount of PEBW can lead to either accurate or slightly overestimated distance judgments (for the five-meter target distance). The impact does not appear to be caused by simply walking alone since the 8 loop eyes open walking (with 1 PEBW loop) did not show similar improvements. Blind walking, perhaps because it helps participants gain trust, confidence, and familiarity with the task, does have a significant result. Our results suggest that applications or experiments requiring accurate distance judgments in HMDs may be able to reach accurate performance with a significantly long blind walk. Further, our work provides a ceiling for the most amount of PEBW one might want to perform without concern of potentially having significant overestimation.

Future work might explore whether even longer amounts of PEBW might lead to significant overestimations. One unexpected result was that distance judgments appeared to continue to increase over trials despite the extensive 8 loops of PEBW (Figure 4.10). One interpretation of this increase is that even more PEBW walking than our 8 loop condition might produce overestimation of distances. On the other hand, our 4 loop PEBW condition in the previous experiment suggested that performance did not seem to significantly change over trials (Figure 3.10). More work is needed to determine exactly how extensive amounts of PEBW might impact distance judgment results and performance over trials.

Another notable result from this experiment is that that eyes-open walking prior to the experiment did not alter the participant's ability to accurately gauge distance, indicating that subjects can engage in unrestricted walking before the experiment without jeopardizing their distance perception, provided that some degree of PEBW is incorporated into the experimental procedure. We hypothesized that participants who experienced more eyes-open walking before the PEBW would exhibit greater walking distances than those only exposed to PEBW. However, our findings contradicted this assumption, revealing no differences between the groups. One plausible interpretation could be that the effect of the preliminary eyes-open walking is eliminated due to the intense sensory isolation that follows during the 1 loop of PEBW after the 8 loops of eyes-open walking. As far as we know, this is the first study which examines this topic. The result is important because it removes one potential confounding factor that might need to be considered when comparing distance judgment studies. For example, we wouldn't expect significantly different results between an experiment where participants had to walk a great distance to the study compared to those who might have had to walk less immediately prior to the study.

The see-through condition, where participants completed 8 loops of video see-through mode with their eyes open under VR HMD, also produced interesting results. We investigated this because we hypothesized that walking while wearing the HMD, even when it was configured in a see-through mode, might help participants gain confidence and trust in the device itself and therefore result in longer distance judgments. The results show some improvement in distance judgment compared to the 1 PEBW condition and the 8 loops real world eyes-open with 1 PEBW loop condition. These results suggest that simply having participants walk for a significant distance in a see-through mode while wearing the HMD results in better distance judgments than the traditional several minutes of blind walking that experimenters typically use in their studies. The 8 loops of see-through HMD walking is very easy to perform compared to PEBW because it would not necessarily require a second person to ensure safety. Further, 8 loops of see-through HMD walking is very fast because participants simply walk—they do not need to be repeatedly stopped and rotated when they approach a wall. Further, the change in performance over trials in the see-through condition also seems roughly similar to that in the other conditions with 1 PEBW loop. Even though further statistical analysis was done and showed there are no significant differences between 1 loop of PEBW and 8 loops of see-through mode, the results suggest that video see-through mode can be a suitable replacement for PEBW based on our results.

### 4.2.2 Walking Velocity

Our comprehensive data collection allowed us to calculate the 99th percentile speed of participants during each trial and their 99th percentile blind walking velocity during each loop of PEBW in the hallway, as showcased in Figures 4.11 and 4.14.

We opted for the 99th percentile of velocity instead of the average velocity in our study to focus on participants' peak performance, which is more indicative of the effects of PEBW (Perceived Exertion Blind Walk). This approach excludes the initial and final phases of the blind walking task, where velocities are inherently lower and not representative of the participant's maximal confidence and capability. By analyzing the peak velocities, we gain insights into how participants approach their maximum velocity, reflecting their highest confidence during the PEBW and direct blind walk tasks.

To ensure accuracy, we excluded the top 1% of the data to account for any potential anomalies or inaccuracies in the Meta Quest Pro's tracking system. This step helps to eliminate outliers that could be due to unexpected movements or system errors. Furthermore, we carefully reviewed each participant's individual data during the direct blind walk to confirm there were no discrepancies. This thorough checking process also ensures that, after data filtering, each participant's dataset contains at least 100 data points, which is critical for the reliable functioning of the algorithm in our 99th

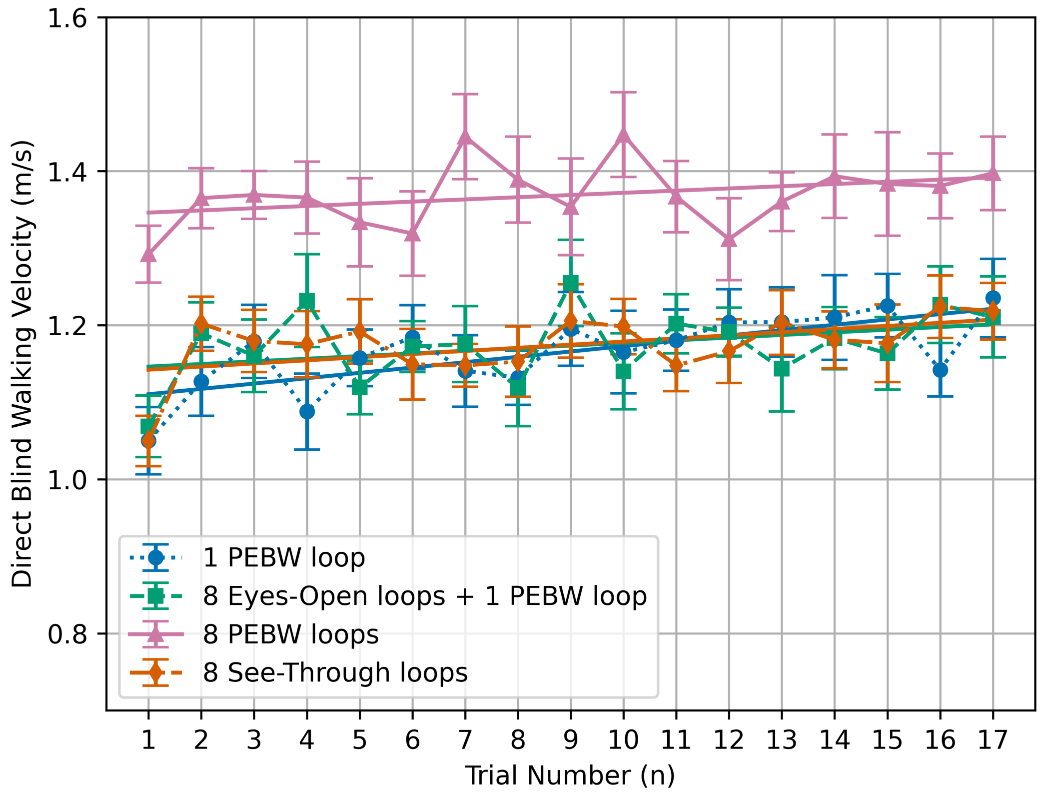


**Figure 4.11:** Average 99th Percentile of Participants Walking Speed During Each Trial (Velocities below 0.3 m/s were removed). Error bars represent ±1 SEM.

percentile analysis method.

In our experiments, target distances were randomly distributed across trials. To better understand the relationship between each trial's velocity and target distance, we plotted the average target distance encountered in each trial for every condition. This representation, shown in Figure 4.12, helps to elucidate the variations and patterns in velocity across different trials.

We hypothesized that participants who walk faster during the PEBW would exhibit greater walking accuracy, characterized by fewer instances of stumbling and a less

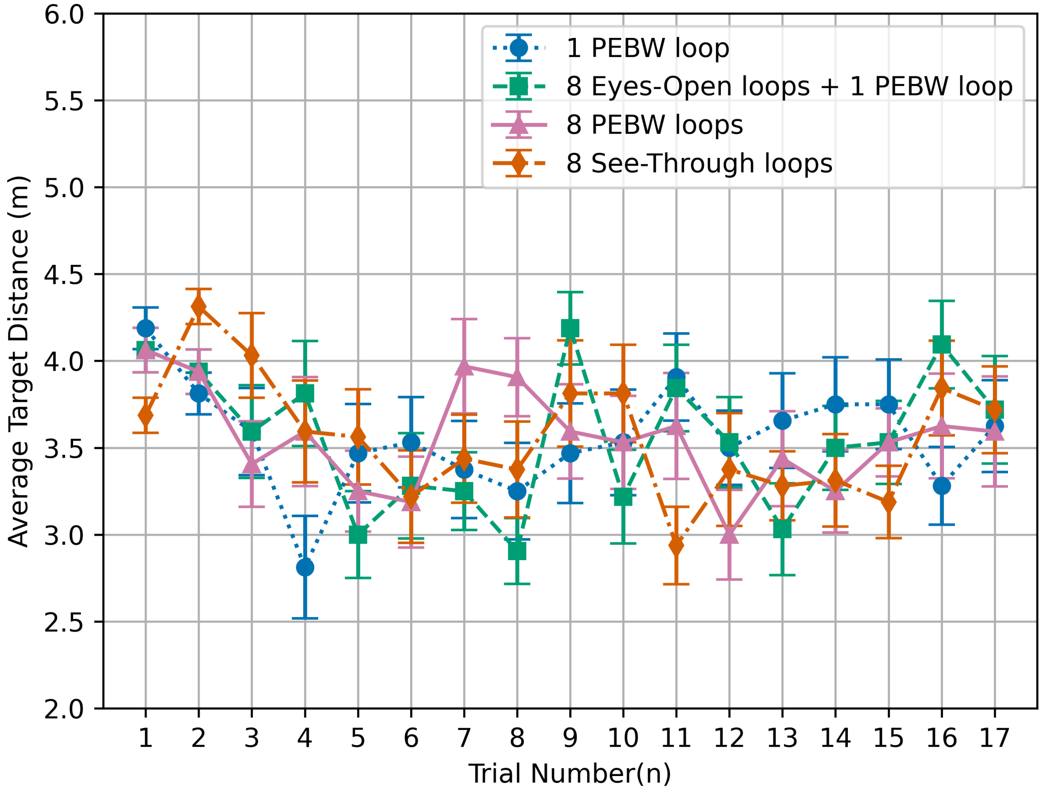


**Figure 4.12:** Average target distances randomness over trials. Error bars represent ±1 SEM.

zigzagging path. This led us to conduct an in-depth analysis of walking patterns during the PEBW, specifically examining the frequency of turns made under each condition and during each loop around the hallway. A faster walking pace may serve as an indicator of participants' comfort during the PEBW. Increased comfort could, in turn, result in reduced drifting and fewer turns throughout the PEBW duration. Additionally, we hypothesized that participants who had more turns during the PEBW may experience heightened anxiety due to frequent directional adjustments. This anxiety could potentially lead to more cautious direct blind walking behavior throughout the experiment, ultimately resulting in greater underestimation of perceived distance

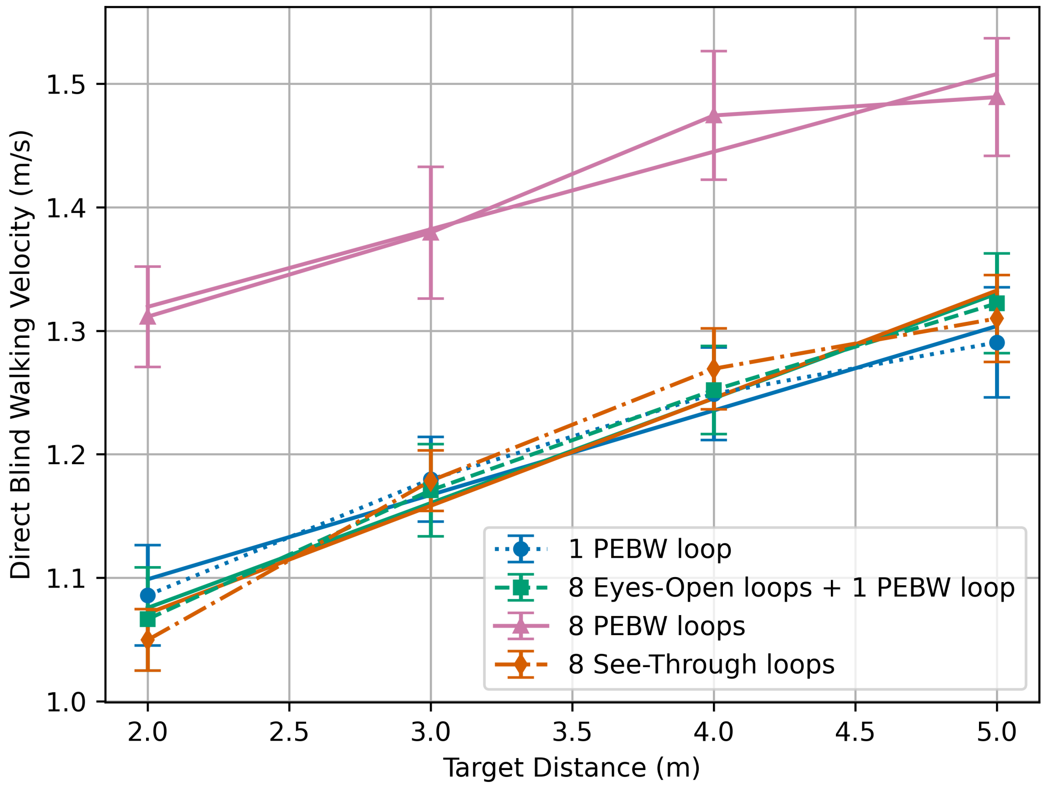


**Figure 4.13:** Average 99th Percentile of Participants Walking Speed During Each Target Distance (Velocities below 0.3 m/s were removed). Error bars represent ±1 SEM.

to the target.

These findings suggest that an increase in participants' blind walking velocity and a decrease in the number of turns potentially promote a sense of trust over an extended PEBW exposure. Based on these findings, the participants' 99th percentile speed across the 17 trials of direct blind walking, as displayed in Figure 4.11, demonstrated a consistent increase. Remarkably, for the 8 loops condition, participants' initial trial speed was approximately 1.3 m/s, unlike other conditions which had around 1.1 m/s in their first trial.

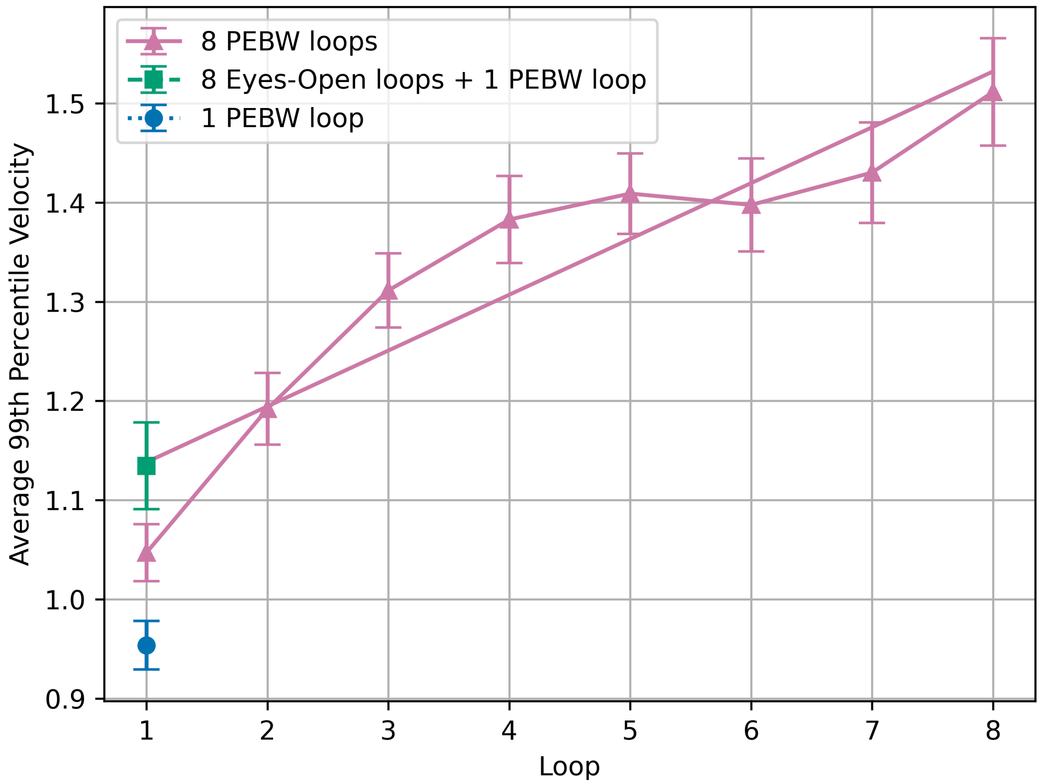


**Figure 4.14:** Participants' Average 99th Percentile Velocity during each Loop of PEBW (Velocities below 0.3 m/s were removed).

To address spikes and declines observed in some trials, we plotted the average randomized target distance for each trial in Figure 4.12. From this, we can see that during spikes, such as the one in trial 7 for the 8-loop condition, the average target distance was much higher compared to other trials. This can explain some of the spikes, as the larger walking distance gives participants more time to reach their maximum velocity. Conversely, there may be a smaller walking distance in instances where declines are observed, causing participants to walk more slowly. As they do not have enough time to reach a higher velocity, the result is lower for those specific trials.

These intriguing parallels in velocity led us to hypothesize that this similarity could contribute to the observed discrepancies in participants' judged distance during various numbers of loops for PEBW. We believe that participants exhibiting increased speed may expect to cover greater distances due to diminished anxiety associated with being blindfolded and a reduced fear of colliding with obstacles. Additionally, we can see the speed for the first loop of PEBW is also between 0.9 and 1.2 m/s which is similar to the speed of other conditions in the first trial during the experiment except 8 loops of PEBW during the experiment since prior to the actual experiment participants extremely practiced blind walking during the 8 loops of PEBW.

### 4.2.3 Walking Patterns and PEBW Turns

We were also able to plot the walking pathway of participants individually along the hallway's PEBW route as seen in Figure 4.15 and walking pathway during the experiment in the VR lab (Figure 4.16). Furthermore, this dataset enabled us to measure the overall 99th percentile walking velocity during each of the 8 loops, providing insights into how repeated loops might influence participants' walking speed. These results are unique because we are unaware of any other previous work that reports or measures walking patterns during PEBW.

Our computational program helped with the automation of turning point calculation. It did so by evaluating instances of participant velocity reduction and significant

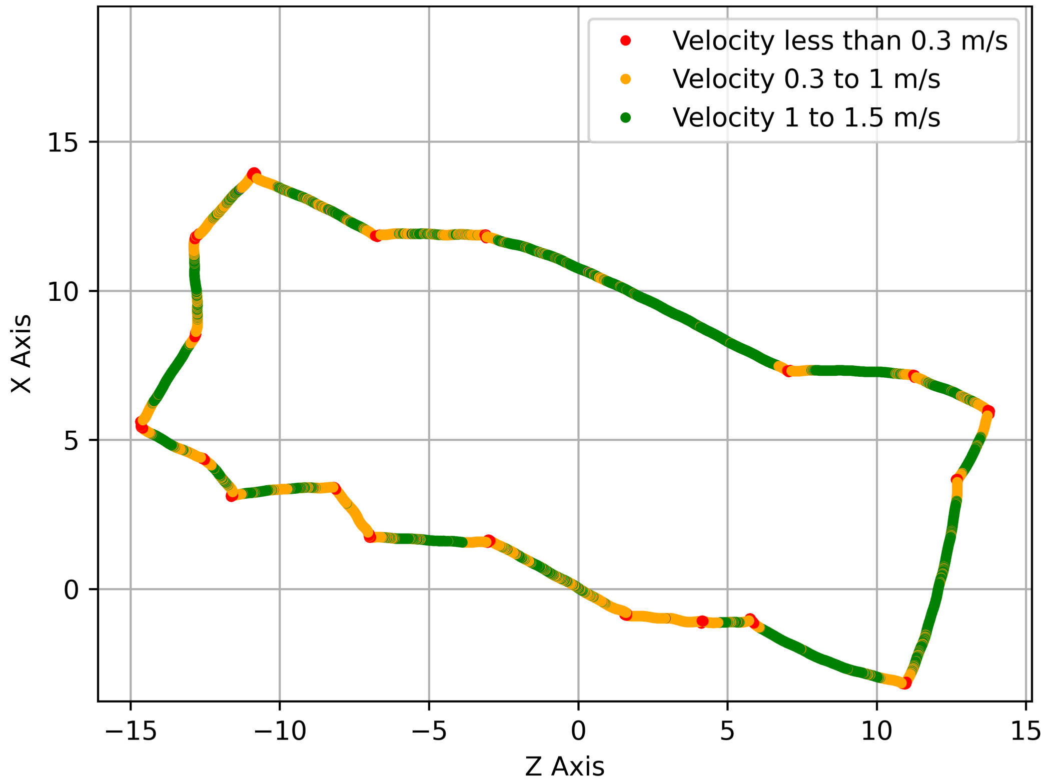


**Figure 4.15:** Participant's walking pathway during 1 PEBW loop.

angular deviation across specific frames. A comparative analysis of the turning points as pinpointed by our automated system was visualized in Figure 4.17. We verified these turning points by checking if they matched with the manual turning points. The algorithm will be discussed in more detail in Chapter 5 and Section 5.4.

We calculated the average number of turns made by participants in each loop using a computational method tailored to their specific conditions. In particular, during the eight loops of the special condition, we found that participants made fewer turns as they grew more accustomed to walking blindfolded. These findings are illustrated in Figure 4.18.

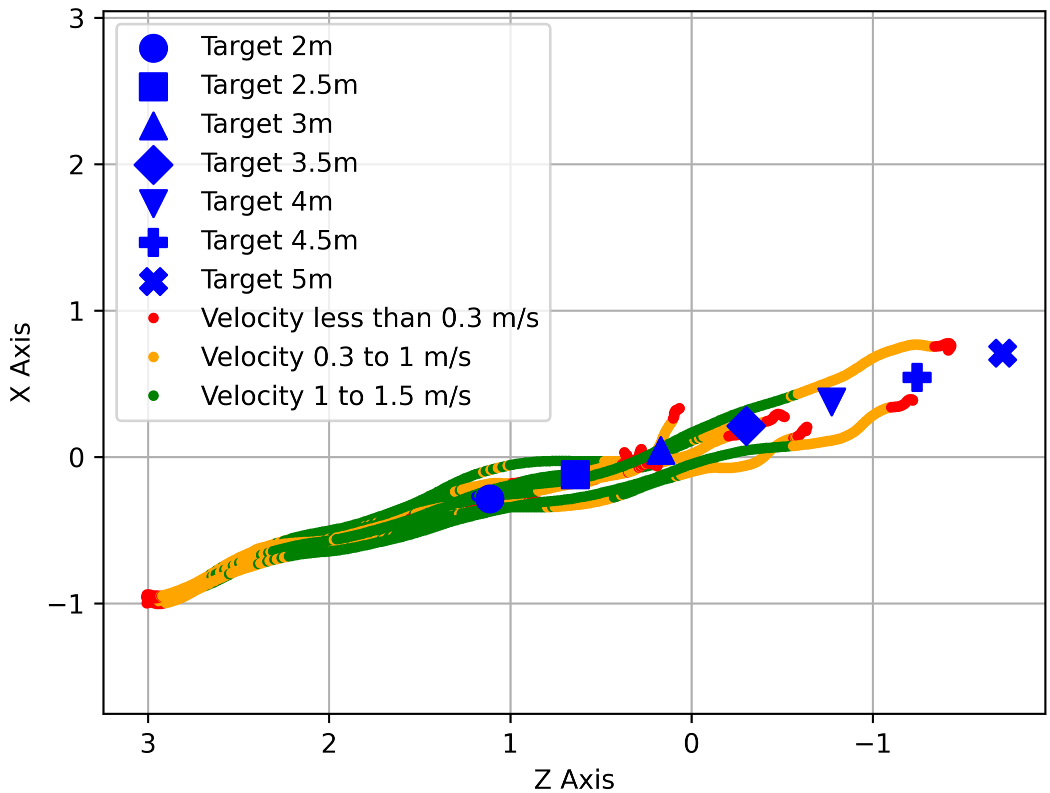


**Figure 4.16:** Participant's walking pathway during the distance judgment experiment in the VR lab.

By observing the walking patterns of participants during PEBW in the hallway as seen in Figure 4.15, we noted that the 99th percentile velocity along the hallway over the loops for 8 PEBW loops condition, shown in Figure 4.14, progressively increased with each PEBW loop. Moreover, the number of turns made by participants gradually reduced over each loop, as indicated in Figure 4.18. We believe that the number of turning points decreased over time for two reasons. First, participants likely walked straighter as they completed more loops. Second, participants may have also become better at correctly responding to the direction that the experimenter pointed them in after each turn. The experimenter did not intentionally do anything different between

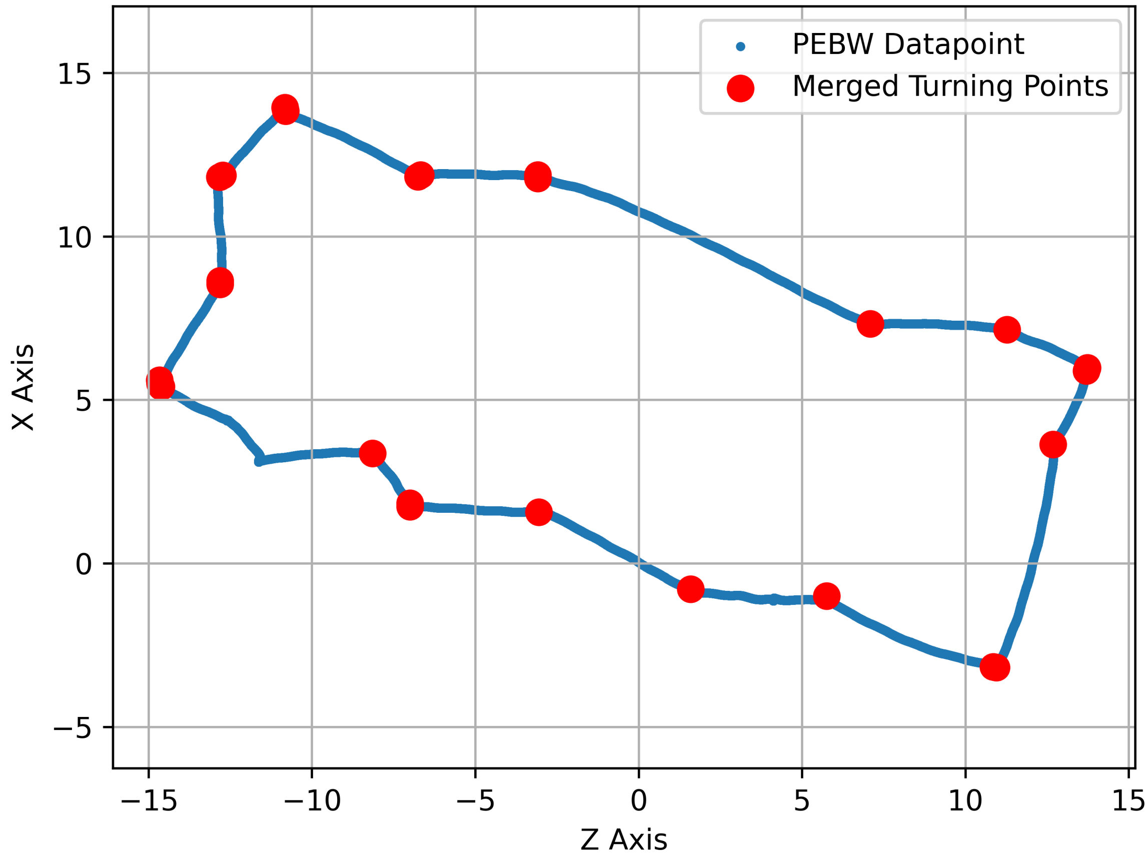


**Figure 4.17:** Participant's automated turning points during 1 PEBW loop

the conditions besides stopping participants when they got close to a wall and then turning them in a safe walking direction.

### 4.2.4 Duration of Direct Blind Walk and Step Size

Moreover, similar to the previous experiment in Chapter 3, we analyzed the duration of direct blind walks within each trial. Mirroring the trends identified in the previous experiment, a similar pattern was observed here as well. As the trials progressed, the duration of the participants' direct blind walk consistently decreased, as demonstrated

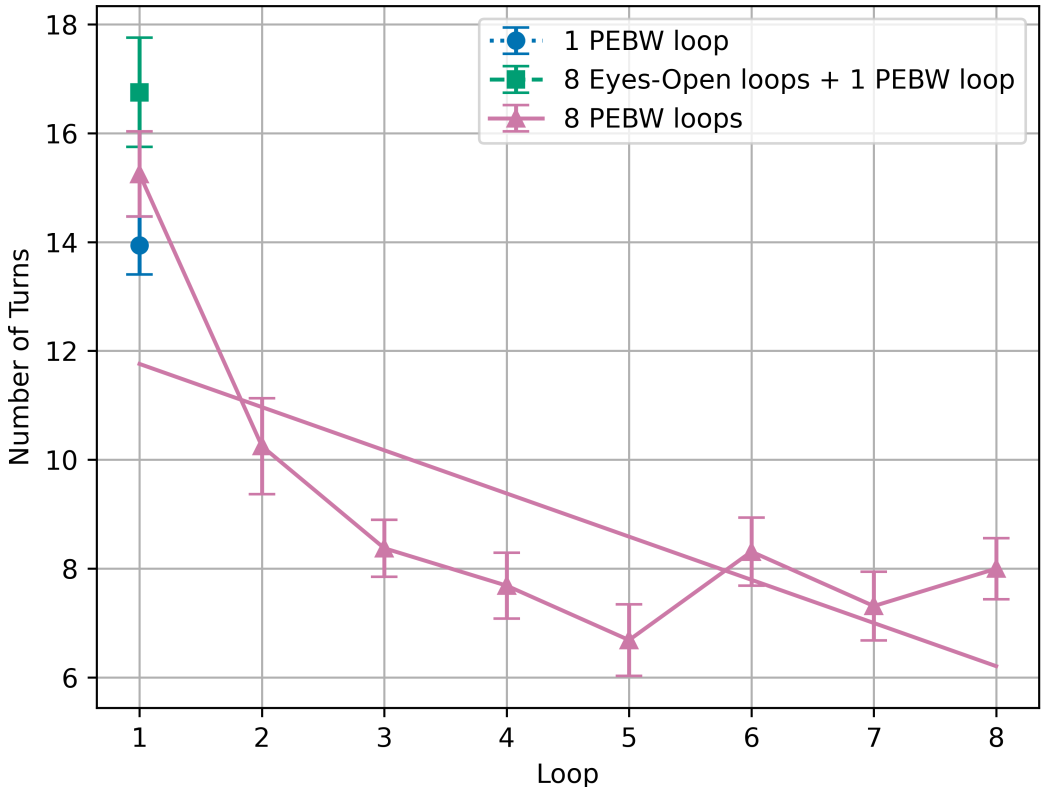


**Figure 4.18:** Number of turning points during PEBW in each loop. 10 Degree threshold and velocity stop threshold is 0.3 m/s

in Figure 4.19. In their initial trial, participants typically took longer to start the direct blind walk. This delay can be attributed to initial hesitancy and the instruction given, which prompted a slight delay before starting.

We also analyzed the approximate median and maximum length of steps for each target distance, as depicted in Figures 4.21 and 4.22, for each condition based on the repetition of local minima in their Y-axis data. Since participants exhibit the shortest height at the initial action of their gait walking pattern, we processed their data individually in Figure 4.20. We then examined the distance they covered along their X and Z axes and calculated the Euclidean distance between these distances.

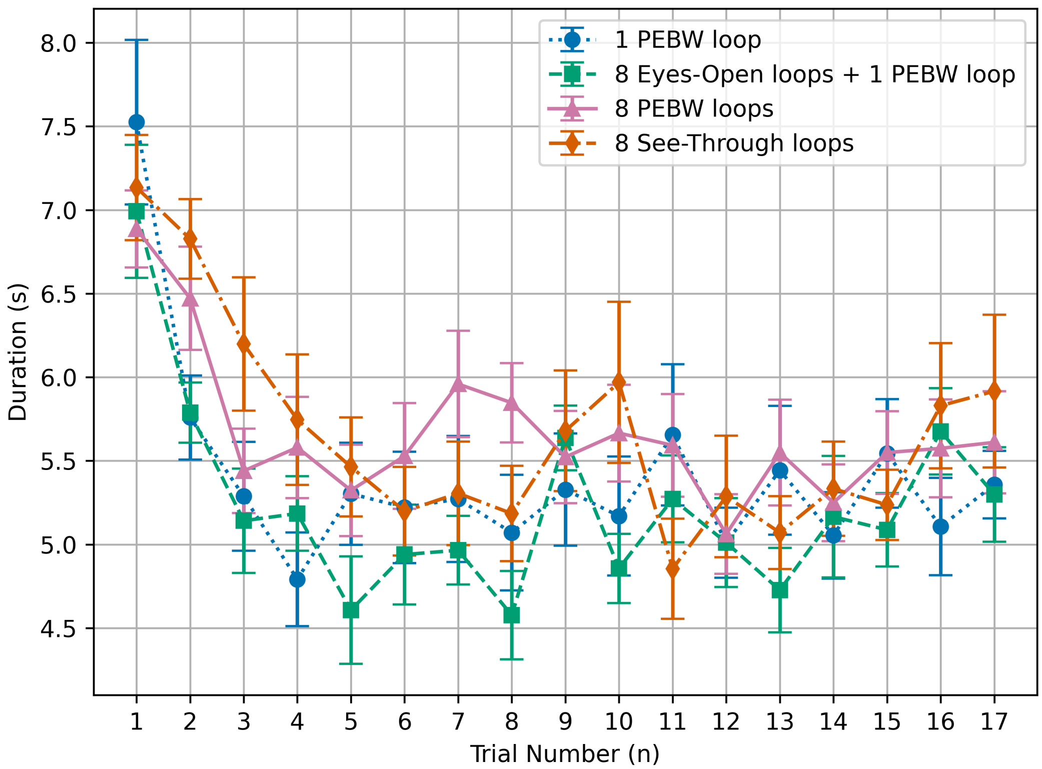


**Figure 4.19:** The amount of time to complete a trial was reduced as the experiment progressed. Error bars represent ±1 SEM.

Interestingly, the step length for 8 PEBW is significantly larger compared to other conditions. Further exploration of these patterns could enhance our understanding of distance perception and gait dynamics in virtual environments. The full description of the algorithm was explained in Chapter 5 and Section 5.5.

Additionally, through our calculation of both the maximum and median walking step lengths based on each target distance, we observed a distinct pattern in the 8-loops of PEBW condition, where participants exhibited much larger step lengths. Furthermore, across almost all conditions, longer target distances corresponded to larger lengths of direct blind walk steps, as depicted in Figure 4.21 and 4.22. Smaller steps

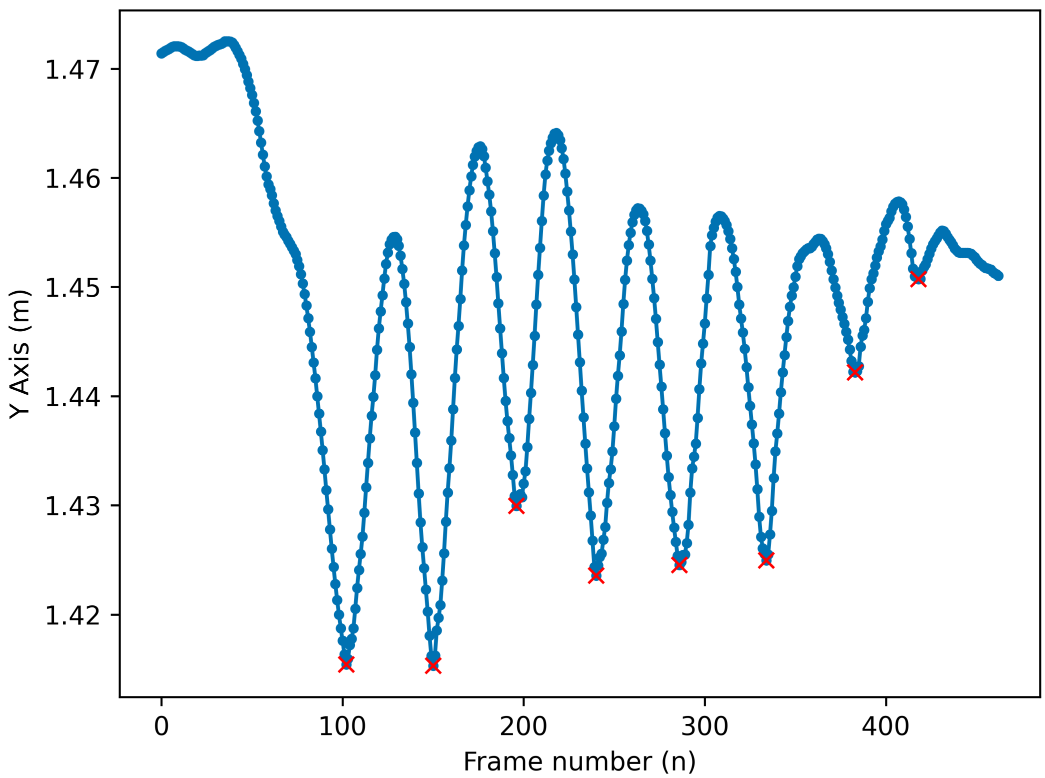


**Figure 4.20:** The step detection algorithm output for one participants and one trial after processing the signal and selecting local minima

for shorter distances were largely expected because many people may take smaller steps when speeding up and slowing down. In the shorter distances, participants are not walking far enough to reach their comfortable walking speed and take a full step.

## 4.3 Discussion

Recent developments in head-mounted display (HMD) technologies have stimulated studies focusing on the perception of distances in virtual environments. Kelly et al. [22] embarked on such an investigation, examining the comparative performances

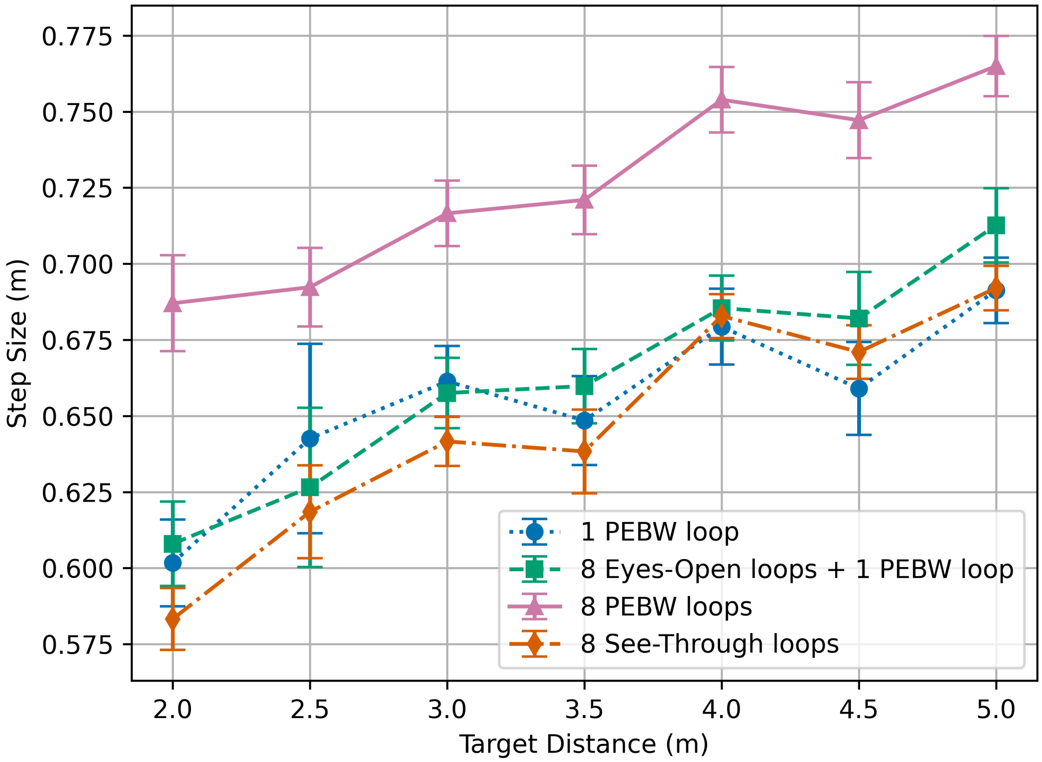


**Figure 4.21:** Max walking steps length during direct blind walk based on each target distance. Error bars represent ±1 SEM.

of Meta Quest 1 and Quest 2 devices. Their findings revealed a recurring issue of distance underestimation, amounting to nearly 30% inaccuracy when utilizing a direct blind walking approach, despite the technological advancements embedded in these devices.

Our study highlights the influence of the blind walking activity conducted prior to the experiment. This PEBW phase serves a crucial purpose, providing a training ground where participants acclimate to the process of blind walking within a non-virtual, controlled environment.

Our research findings underscore the significant impact of the PEBW procedure on

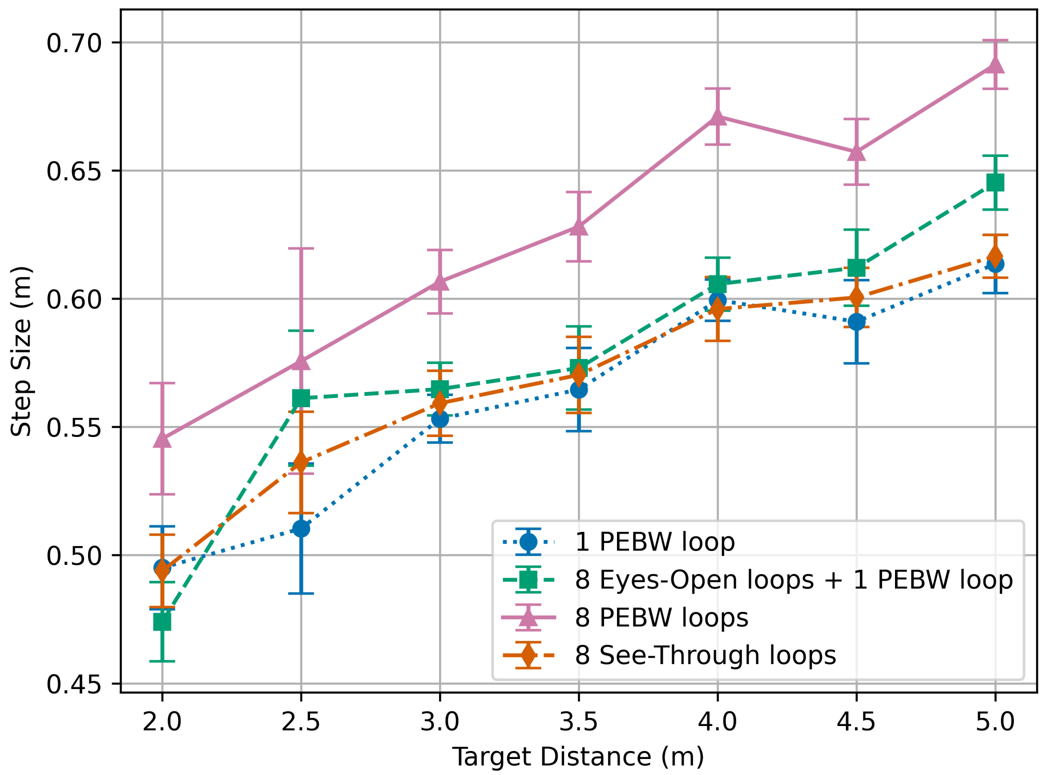


**Figure 4.22:** Median walking steps length during direct blind walk based on each target distance. Error bars represent ±1 SEM.

participants' perceived distance in VR. The adoption of this procedure led to the achievement of an outstanding overall accuracy rate exceeding 97% across four PEBW loops in Chapter 3. Remarkably, when the loops were increased to eight in our second experiment, participants were even seen to overestimate distances, a striking contrast to Kelly et al.'s observed underestimation phenomenon. This suggests that our PEBW method not only mitigates the underestimation of distance often experienced in virtual environments, but could also potentially recalibrate perception to the point of overestimation.

Kelly et al. [17] conducted a comprehensive review, examining the influence of various

HMDs properties, such as field of view (FOV) and resolution, on distance perception in VR. They examined a range of HMDs, from older models to the more recent Quest 1 and Quest 2, and found consistent underestimations of distance, with an average of 30% across all HMDs. In contrast, our study utilized the more technologically advanced Meta Quest Pro. Although the core technology of Quest Pro shares many similarities with the Quest 2, there are significant differences. The Quest Pro boasts an improved FOV of 106ºH × 96ºV, compared to Quest 2's 96ºH × 96ºV. Furthermore, the Quest Pro, although heavier at 722g compared to the Quest 2's 503g, offers a more immersive experience due to its technical superiority. Contrary to the findings of Kelly et al. [17], our study showed a marked improvement in distance perception accuracy using Meta Quest Pro and having PEBW prior to the experiment. With the use of the Quest-Pro and the integration of the PEBW task, our participants achieved an accuracy rate of over 80%. This substantial enhancement of distance perception accuracy suggests a complex interplay between HMD properties and experimental protocols. Our results illuminate the potential of utilizing the advanced specifications of the Meta Quest Pro, combined with specific training tasks such as the PEBW. The wider FOV might provide more spatial information, thus enhancing the users' perception of distance. Furthermore, using the PEBW task likely serves as a form of calibration, assisting users in translating real-world experiences to VR spatial perception. Our findings, therefore, highlight the importance of pre-experiment procedures in distance perception in VR. Beyond HMD specifications, it is apparent that the experimental design and specific training tasks can significantly change distance perception accuracy.

Observation shows participants' eyes-open walking prior to the PEBW did not impact participants' distance perception in VR. This might be because people are used to walking with their eyes open everyday. This habitual behavior could mean that eyes-open walking doesn't significantly enhance participants' confidence when they do direct blind walking in a VR environment. They likely trust their own eyesight more than the VR HMD. Additionally, performing PEBW after eyes-open walking might have overshadowed any effects from the real-world walking experience. This suggests that eyes-open walking before PEBW didn't change the outcomes compared to our control condition of just one PEBW loop.

The advanced cameras and video see-through capabilities available in newer VR HMD devices like the Quest Pro open up interesting possibilities for research. Our results demonstrate the potential of using see-through mode pre-walking as an alternative to PEBW. Despite not being exposed to PEBW conditions, participants in the see-through condition exhibited less underestimation of distances using direct blind walking than those who performed just one loop of PEBW.

This finding suggests that the see-through visual experience may enhance users' comfort and trust in VR, even without having a PEBW task. We hypothesize two potential mechanisms for this effect. First, the exposure to real-world visualization through the VR headset before the experiment may increase familiarity and confidence with using the device. Second, viewing their actual surroundings through the HMD could build users' trust that the external environment is safe and obstacle-free during direct blind walking tasks.

Optimizing VR pre-experiment exposures like see-through walking to change and improve distance accuracy could significantly benefit training and simulation applications. Further examination of these exciting tools and features could lead to a more realistic experience and closer to the actual distance of targets in a VR environment.

Philbeck et al. [40] observed that participants' blind walking velocity increased over successive trials in their Experiment 2 and attributed this increase to participants gaining confidence with more blind walking practice; other factors could also potentially contribute to the velocity changes. These include participants becoming more adapted and comfortable with the task through repeated trials, growing familiarity with the procedures and environment, and differences in target distances between trials influencing measured speeds. These factors of adaptation, familiarity, order effects, and distance variation provide plausible explanations for the observed changes in blind walking velocity across trials.

In contrast to Moheler's study [35], Our work has shown that participants exposed to increased PEBW conditions adapt by increasing their walking velocity and step size. These observations highlight the potential for gait adaptation with sufficient experience. We hypothesize that the initial reductions in step size and walking speed may come from a lack of familiarity with both blind walking and the use of VR HMDs. With extensive exposure to PEBW, we showed that participants will adapt their walking gait and velocity accordingly.

Our study results also align with Philbeck's findings, showing increases in PEBW velocity over loops and after the PEBW during the direct blind walk trials. The gradual velocity increases can further be connected to participants' growing confidence, as evidenced by the larger step sizes exhibited in conditions with more PEBW loops in Figures 4.21 and 4.22. The extreme amount of PEBW (8 loops of PEBW) appears to boost participants' assurance and trust, enabling faster walking speeds.

## 4.4 Limitations and Challenges

While this research makes important contributions to understanding pre-experiment walking and distance perception in virtual reality, there remain opportunities to build on these findings through additional research. One limitation of the current work is that it focuses solely on distance perception within virtual environments. An important extension would be to conduct similar real-world experiments analyzing the effects of PEBW on physical distance judgments. Comparing real and virtual conditions would provide greater insight into how pre-experiment walking influences compatible effects across environments.

Additionally, the current research examined pre-experiment walking using VR HMDs in see-through mode but did not test effects on distance judgments made in augmented reality where virtual objects are overlaid on the physical environment. Further research should explore whether familiarization from see-through walking transfers to improved distance perception in augmented reality settings more than in virtual environments. Testing a range of see-through walking durations prior to augmented reality tasks could elucidate this relationship. It might be possible to see more effect of pre-experiment walking using see-through mode if the distance perception experiment is conducted in an augmented reality environment.

Understanding the boundary conditions of pre-experiment walking effects across virtual, augmented, and real environments remains an open research question. As virtual and augmented technologies continue to advance, comprehensive research accounting for crossover effects between environments will be very helpful for spatial judgment comparisons across various studies and research. These connections will help us better understand how people judge distance and their behavior and improve training and optimize applications requiring accurate distance perception, such as medical, military, and educational training applications.

Additionally, a notable limitation in our study is the potential for participants to memorize their walking paths during the PEBW due to consistent walking directions. Introducing randomized walking directions would be advantageous to address this in future studies. This change would help prevent participants from relying on their memory of the path, ensuring that their distance estimations in VR are not biased by prior knowledge of the walking route.

## 4.5 Conclusion

In our second set of experiments, we extended our focus on the influence of PEBW, similar to our previous work. This time, however, we introduced variable scenarios during the pre-experiment walk. For instance, we explored the impact of having participants engage in extended periods of normal walking before doing PEBW procedures and distance perception experiments. We also adapted our methodology to accommodate advances in VR HMDs. Specifically, we utilized the see-through mode feature of the Meta Quest Pro to examine how VR familiarization using this feature impacts distance perception in VR.

Our results place particular emphasis on the comprehensive reporting of PEBW tasks. Depending on the conditions set for PEBW, we identified multiple factors contributing to varying outcomes when PEBW is either present, duration modified, or limited. These factors include the participants' walking speed, which seemed to be influenced by reduced anxiety when walking blindfolded, and increased confidence during direct blind walks due to prior familiarization with the task. Moreover, our data suggest that participants' behavior, including the number of turns taken and step size, experience adaptation during the walking task.

# Chapter 5

# Algorithms and Data Analysis Methods

This chapter explains the data analysis methods used for the results in Chapter 4. We'll cover algorithms like the velocity calculator, turning detection, and step size analysis. Knowing how these algorithms work will help researchers understand the results in Chapter 4 better, and more importantly, it can be helpful for letting other researchers be able to reproduce them or use them to report metrics in their papers.

## 5.1 Data Collection in VR Quest Pro

As discussed in chapter 4, our VR program gathers crucial data from participants, including their X, Y, Z coordinates, timing data, and direction. This comprehensive data collection has allowed for robust analysis, offering us significant insights into participant behavior both during the pre-experiment procedure and the main experiment.

The VR Quest-Pro operates at approximately 70 frames per second. Given this frame rate, we accumulate extensive data for every participant. We have categorized this data into two segments:

1. Data from the pre-experiment procedures conducted in the hallway.

2. Data from the primary experiment carried out in our VR lab.

Before starting both phases of the experiment, equipment calibration was performed to ensure the accuracy and reliability of the data collected.

The Meta Quest Pro features inside-out tracking, employing built-in cameras and sensors to determine its position. This self-contained system is both convenient and user-friendly. However, there's a potential trade-off in precision compared to external tracking systems. To maintain optimal tracking accuracy, the device continually refines its tracking by observing its environment, measuring its movement, and merging data from various sensors. To achieve the most accurate tracking, it is recommended to use the device in a well-lit setting, avoid environments with reflective surfaces, and make necessary adjustments if discrepancies are detected. The Meta Quest Pro employs an advanced tracking system combining infrared cameras, high-resolution cameras, and eye tracking to achieve comprehensive 6DoF (six degrees of freedom) tracking. This system allows for precise tracking of head and controller movements in all axes, including pitch, yaw, and roll, as well as lateral and vertical movements. The infrared cameras primarily focus on controller positioning, the high-resolution cameras on the headset and hand positioning, and the eye tracking system enhance overall tracking accuracy. While our study was conducted using the Meta Quest Pro, research by Holzwarth et al. [14] on the Oculus Quest 2, a related model in the Meta Quest series, indicates high accuracy in vertical tracking for these head-mounted displays (HMDs). This finding may provide useful insights into the tracking capabilities of the Meta Quest family of HMDs.

Post-experiment, we collated two distinct datasets for each participant, reflecting their actions and interactions during the pre-experiment and main experiment phases. This information was essential for our experimental analysis and understanding of participant behavior throughout the experiment.

## 5.2 Cumulative VS Euclidean Distance in VR Distance Estimation

Typically, VR distance estimations rely on the Euclidean distance formula given by

$$d = \sqrt{(x_2 - x_1)^2 + (z_2 - z_1)^2}$$

where $(x_1, z_1)$ and $(x_2, z_2)$ are the coordinates of two points in a two-dimensional space.

Given our collection of participants' instantaneous data during the VR lab experiments, we considered an alternative method for distance calculation. Instead of solely relying on the Euclidean distance between the start and end points, we proposed calculating the distance between each pair of consecutive frames and then summing these distances to get a cumulative value. This approach was supposed to be potentially more accurate due to the direct blind walking method: participants may not always walk straight toward the target. They could drift to the right or left from the intended path due to being blindfolded.

This observed behavior led us to question our traditional calculation methods. If we account for every tiny deviation from the straight line by summing up these small distances, our estimations might align more closely with the actual distance covered by participants. Since participants walk blindfolded, they might be unaware of minor changes in their direction. This factor could significantly influence the commonly observed underestimation in their distance estimations.

However, in Chapter 4, our results show there was only a small increase in participants' estimated distance in the cumulative version if we directly compare the two methods results.

| **Condition** | **Target Dist (m)** | **Normal (%)** | **Cumulative (%)** |
|---|---|---|---|
| 1 PEBW | 2.0 | 81.58 | 84.63 |
| | 3.0 | 83.86 | 87.07 |
| | 4.0 | 84.01 | 85.92 |
| | 5.0 | 86.77 | 88.64 |
| 8 Eyes-Open 1 PEBW | 2.0 | 82.26 | 85.48 |
| | 3.0 | 80.86 | 82.92 |
| | 4.0 | 84.00 | 85.69 |
| | 5.0 | 85.56 | 87.06 |
| 8 PEBW | 2.0 | 99.76 | 103.27 |
| | 3.0 | 100.99 | 103.52 |
| | 4.0 | 100.22 | 102.04 |
| | 5.0 | 104.99 | 106.65 |
| 8 See-Through | 2.0 | 86.43 | 89.82 |
| | 3.0 | 85.61 | 88.37 |
| | 4.0 | 88.37 | 90.45 |
| | 5.0 | 92.84 | 94.64 |

**Table 5.1**
Comparison of accuracy for each target distance between the normal and cumulative methods

| **Condition** | **Normal Method (%)** | **Cumulative Method (%)** |
|---|---|---|
| 1 PEBW | 84.62 | 86.57 |
| 8 Eyes-Open + 1 PEBW | 83.64 | 85.29 |
| 8 PEBW | 102.02 | 103.87 |
| 8 See-Through | 89.10 | 90.82 |

**Table 5.2**
Comparison of overall accuracies in all four conditions for each method

## 5.3 Velocity Calculation Algorithm

In the context of velocity algorithms, we observed the availability of data points. This allowed us to calculate the Euclidean distance, $\Delta x$, between two consecutive frames. Given the presence of instantaneous time frames, the instantaneous velocities can be determined using the formula:

$$v = \frac{\Delta x}{\Delta t} \tag{5.1}$$

where $v$ represents the instantaneous velocity and $\Delta t$ denotes the change in time.

The primary motivation for calculating velocity is to assess participants' adaptation throughout both the pre-experiment procedure and the main experiments. To address potential inconsistencies introduced by the tracking system, we used the 99th percentile of the instantaneous velocities to determine the peak velocity achieved by participants during their direct blind walking in the experiment for each trial. While some researchers have employed average velocities to measure participants' behavior in other studies [40], we thought the 99th percentile of velocity provided a more accurate representation. This is because the average velocity might be skewed by pauses at the start and end of a walk or by adjustments made at the conclusion of the direct blind walk. Thus, we concluded that using the 99th percentile of walking velocity for each direct blind walk trial was more appropriate. Additionally, avoiding the use of maximum velocity helps prevent unexpected fluctuations in the data, thereby reducing the risk of inaccurate results and any unexpected small inaccuracies in the tracking system. To prevent stopping at the beginning and end of the direct blind walk for each trial, we removed all the velocity data that were below 0.3 m/s. Additionally, we checked the number of data points for each participant to ensure they had more than 100 data points in each trial, even after removing velocity limitations (velocities below 0.3 m/s). This gave us confidence that for short target distances, like 2 meters, we still had enough data to accurately use the 99th percentile of instantaneous velocity for our analysis during the direct blind walk experiments.

### 5.3.1 Velocity Per Loop

To analyze participants' walking patterns and velocity adaptation during PEBW, we developed a Loop Counter algorithm to detect completed loops from the participant tracking data. The algorithm processes the timestamped coordinate data, incrementing the loop count when two criteria are met:

1. The participant has walked for at least 30 seconds since the start of the current loop. Since all participants walk counterclockwise, they will not return to their original starting point unless they complete the whole loop around the hallway and have enough time to get distance from their starting point after 30 seconds.
2. The participant's proximity is within 1.5 meters of their original starting position. This 1.5 meters threshold was selected, knowing participants traverse the

rectangular hallway loop but may not return to the exact initial location. Given the narrow 2.3 meters hallway width, participants will pass within 1.5 meters on each loop. The algorithm initializes the loop count at one and sets the loop start time to the first data point. It then iterates through each timestamped row, checking for the duration and proximity conditions to be met.

If both criteria are satisfied, the loop count is incremented, and the loop start time is getting updated. This automated loop detection enables detailed analysis of walking velocity and patterns across successive loops during the PEBW phase, providing insights into participant adaptation and performance over time.

## 5.4 Turning Points Detector Algorithm

In Chapter 4, we have mentioned we could detect walking patterns and how participants walked during the pre-experiment walk, especially for different types of PEBW. However, in addition to the instantaneous data collected, we have also counted manually when participants stopped, and we have adjusted their blind walking direction during the PEBW.

The algorithm detects turning points in participants' walking paths by analyzing their velocity and position data. Initially, the algorithm calculates the speed of a participant by observing the changes in their coordinates over time using a sliding window

**Algorithm 1** Velocity Calculator and Loop Counter

**Require:** a List of directories containing CSV files (each CSV file contains individual participants' positioning and timing data, and each directory contains all participants CSV file that are in each condition)

**Ensure:** Plot showing average 99th percentile velocity for each loop

```
for each directory in directories do
    for each file in directory do
        Read data from file
        Compute distance between consecutive data points
        Compute instantaneous velocity
        Filter out rows with velocity < 0.3 m/s
        Compute cumulative distance, distance, and time from starting point
        Initialize loop_count ← 1
        Initialize loop_start_time ← data['Time_From_Start'].iloc[0]
        for each i, row in data.iterrows() do
            if Time since loop_start_time > 30 seconds and Distance from start ≤ 1.5 meters then
                Increment loop_count
                Update loop_start_time
            end if
            Assign loop_count to current row
        end for
        Compute 99th percentile velocity for each loop
    end for
    Store velocities for directory
end for
Sort directories based on custom label order
for each directory in sorted directories do
    Compute average velocities and standard errors
    Perform linear regression if applicable
    Plot average velocities with error bars
end for
Display plot
```

approach. Subsequently, it determines the turning points based on the angle of direction change between specific sliding window points and ensures that the speed at these potential turning points is below a predefined threshold. To avoid overcounting due to noise or minor fluctuations in direction, the algorithm merges nearby detected turning points into a singular point.

After identifying these algorithmic turning points, the system cross-references them with manually recorded turning points to assess their accuracy. It computes the distance between each manual point and the algorithm-detected points. If they are within a set proximity, they are considered intersecting. The results are then visualized: walking paths are plotted with both types of turning points, highlighting intersections to indicate areas where the algorithm aligns with manual observations. The outcomes for each walk, detailing the detected turns, are saved in CSV format for further analysis and plotting.

† **turn_threshold:** This parameter, set to 10°, shows the minimum angular change in the direction necessary to qualify as a turn. It acts as a filter to differentiate significant turns from minor fluctuations in direction.

† **min_distance:** With a value of 0.1 meters, it requires the minimum spatial separation between consecutive data points for them to be considered in the turn analysis. This eliminates the influence of minor spatial deviations that might arise from noise, tiny deviations, or other inaccuracies.

† **merge_distance:** Set at 1.5 meters, this parameter determines the proximity threshold within which sequential turns can be seen into a singular turn event. Knowing one turn should not be counted as several turns is crucial.

† **velocity_threshold:** Defined at a value of 0.3 meters per second, this threshold

prescribes the max velocity a segment should maintain for it to be accounted for in the turn detection process. This ensures that only velocities below this value should be considered for turning detection.

† **window_size:** Defined at a value of 70 frames. This value is approximately equivalent to 1 second of data. This time span is ideal for recognizing a turning action. Using a very short window, such as only two consecutive frames, might not be sufficient to capture normal angle variations, like a 10-degree turn. However, with a window size of 70 frames, we are better positioned to detect genuine turns. Furthermore, to ensure we avoid capturing repetitive turning points, we have incorporated a merging distance mechanism, as explained earlier.

**Algorithm 2** Calculate Speeds from Coordinates

```
procedure CALCULATE_SPEED(x_coords, z_coords, time_values, window_size)
    speeds ← list of zeros of length window_size
    for each coordinate from window_size to end do
        Calculate distance using x_coords and z_coords
        Calculate speed using distance and time
        Append speed to speeds
    end for
    return speeds
end procedure
```

We were interested in analyzing the ratio of turns to loops to assess participant adaptation during the PEBW experiment. We used computational and manual methods to ensure accuracy in calculating turns. While running the experiment, we collected real-time data and noted instances where participants manually turned. Due to human error, we cross-referenced these manual turns with our computational calculations.

**Algorithm 3** Merge Close Turning Points

```
procedure MERGE_CLOSE_TURNING_POINTS(turning_points, merge_distance)
    Initialize empty list merged_points and merge_count ← 0
    for each point in turning_points do
        Calculate average for close points within merge_distance
        if more than one point was merged then
            merge_count ← merge_count + 1
        end if
    end for
    return merged_points, merge_count
end procedure
```

**Algorithm 4** Count Turns in Coordinates

```
procedure COUNT_TURNS(x_coords, z_coords, threshold_angle, min_distance,
merge_distance, speeds, speed_threshold)
    turns ← 0 and initialize empty list turning_points
    for each coordinate until penultimate do
        Calculate the angle between two points separated by at least min_distance
        if angle > threshold_angle and speed below the speed_threshold then
            turns ← turns + 1
            Add point to turning_points
        end if
    end for
    return turns, turning_points
end procedure
```

Our findings suggest that both methods yield approximately similar results.

However, we chose to rely primarily on computational methods for two reasons. First, manual turning data lacked context regarding the loop number in which participants walked. Second, our computational approach filters out minor directional changes, such as slow walking or hesitation, to avoid false positives. We validated this by visually mapping turning data, confirming the approximate accuracy of our computational approach.

**Algorithm 5** Main Algorithm (Turning Detection)

```
List directories containing data
List manual_directories containing manual data
main_dir ← current directory
for each directory in directories and its corresponding manual_directory do
    Define turn_threshold, min_distance, merge_distance, speed_threshold
    Initialize empty lists results and merge_results
    Create output folder 'turning_points_coords' if not exist
    for each file in files do
        Load file into DataFrame
        Extract x_coords, z_coords, and time_values
        Calculate speeds using CALCULATE_SPEED
        Calculate turns and turning_points using COUNT_TURNS
        Merge close turning points using MERGE_CLOSE_TURNING_POINTS
        Append to results and merge_results
        Save turning_points to CSV in output folder
        Plot x_coords and z_coords
        Overlay turning_points on plot
        Load corresponding manual data
        Overlay manual data on plot as turning_points
        for each manual_coordinate do
            if there's a turning_point within certain distance then
                Mark as intersection
            end if
        end for
        Save intersections count to 'intersection_counts.csv'
    end for
    Save results and merge_results to their respective CSVs
end for
```

## 5.5 Step Detection Algorithm

Another algorithm we have worked on is the step detection algorithm from the Y-axis data of our individual participants through direct blind walking in the lab. The algorithm is tailored to analyze and visualize walking data derived from experimental studies. By employing a Gaussian filter, the Y-axis data undergoes a refinement process, utilizing a smoothing parameter, $\sigma$, set to 0.1. After this refinement, the smoothed data is inverted, transforming valleys into peaks to facilitate the step detection process. This inversion is essential for using the `find_peaks` function from the `scipy.signal` library. Within the peak detection process, two crucial parameters are defined: a *distance* parameter set to 20, ensuring a minimum interval of 20 data points between consecutive peaks, and a *prominence* parameter set to 0.0025, guaranteeing that the detected peaks distinctly stand out from their immediate surroundings. Once steps are detected, the X and Z coordinates are employed to compute the step lengths. Results are subsequently saved into summary CSV files. Concluding the process, the algorithm renders visual representations, illustrating both the maximum and median step lengths across distinct conditions. For enhanced clarity and data variability insights, the standard error of the mean (SEM) is depicted as error bars in the visual outputs.

To ensure this method works correctly, we counted the number of steps for several participants and validated our step detection algorithm through their manual number of steps, and the program correctly calculated the number of steps during the direct blind walk in the experiment. However, our method might also have some limitations, and we are not saying our design is 100% perfect. However, the results are promising due to our validated data. Even though calculating the number of steps is not a new topic, and Caserman et al. [6] calculate the number of steps for participants, our work is also using a similar method but with a more straightforward robust approach using instantaneous position collected data.

Specifically, Caserman et al. [6] propose four algorithms for step detection using the integrated sensors of a head-mounted VR display. Their techniques rely primarily on acceleration signals, applying thresholds and state machines to identify real-time steps. In contrast, our approach leverages the position data, using a more straightforward peak detection method on the vertical position signal to identify steps. While step detection using HMDs has been explored before, our work demonstrates a straightforward yet effective way of achieving it using position information. By comparing our results to manual step counts, we validated the accuracy of this simplified method for gait analysis applications.

**Algorithm 6** Step Analysis and Visualization from Walking Data

**Require:** Paths to condition folders, Y-axis data
**Ensure:** Visualization of step lengths and summaries in CSV files

**Initialize** design variables for visualization (colors, markers, linestyles, labels).
**function** CALCULATE_DISTANCE(point1, point2) **return** $\sqrt{(point1[0] - point2[0])^2 + (point1[1] - point2[1])^2}$
**end function**
**function** DETECT_STEPS(df, sigma, distance, prominence)
    Smooth the Y-axis data using Gaussian filter with parameter $\sigma$.
    Invert the smoothed data.
    Detect peaks using 'find_peaks' with parameters *distance* and *prominence*.
    Filter peaks ensuring they are not within the first and last 30 data points.
**return** Detected peaks.
**end function**
**function** PROCESS_CSV_FILE(file_path)
    Read the CSV file and filter by 'Current_State' = 'EXP_WALK'.
    **for** each unique trial in the CSV **do**
        Extract trial data.
        Detect steps using DETECT_STEPS
        Calculate step lengths between consecutive detected steps.
        Compute and store statistics (median, max) of step lengths.
    **end forreturn** Results with step length statistics for each trial.
**end function**
**for** each condition_folder **do**
    **for** each CSV file in condition_folder **do**
        Process the file using PROCESS_CSV_FILE
        Consolidate results.
    **end for**
**end for**
Visualize maximum and median step lengths across conditions using error bars to depict SEM.

# Chapter 6

# Conclusion

## 6.1 Main results

Based on current evidence, most research utilizes around 3-5 minutes of PEBW, which appears sufficient to mitigate severe underestimation. While no definitive standard exists, inadequate or excessive PEBW can distort results. Ultimately, the appropriate PEBW duration depends on the goals of the research study or application. Nonetheless, comprehensive reporting in research studies is critical so researchers can interpret results appropriately and evaluate comparisons across studies. Further investigation revealed that eyes-open walking prior to PEBW does not impact subsequent distance judgments in VR. This suggests researchers can initiate experiments immediately if PEBW is planned during the pre-experiment procedures. Additionally, exposure to real-world eyes-open walking under VR HMDs using the VR headset's see-through video mode resulted in a similar performance to several minutes of PEBW. This result opens the door to possibly using eyes-open video see through walking as a simpler, easier alternative to pre-experiment blind walking, which requires extra supervision by an additional person for safety. The result highlights that new relatively low-cost video see-through displays may provide new options to enhance spatial judgments and build trust for VR users. Moreover, analysis of our collected data indicates that increased PEBW is associated with faster walking velocities, larger steps, and fewer turns, likely reflecting boosted confidence and comfort during PEBW in the pre-experiment procedure and direct blind walk for the experiment. Based on current evidence, most research utilizes around 3-5 minutes of PEBW, which appears sufficient to mitigate severe underestimation. While no definitive standard exists, inadequate or excessive PEBW can distort results. Ultimately, the appropriate PEBW duration depends on the goals of the research study or application. Nonetheless, comprehensive reporting in research studies is critical so researchers can interpret results appropriately and evaluate comparisons across studies. Further investigation revealed that eyes-open walking prior to PEBW does not impact subsequent distance judgments in VR. This suggests researchers can initiate experiments immediately if PEBW is planned during the pre-experiment procedures. Additionally, exposure to real-world eyes-open walking under VR HMDs using the VR headset's see-through video mode resulted in similar performance to several minutes of PEBW. This result opens the door to possibly using eyes-open video see-through walking as a simpler, easier alternative to pre-experiment blind walking which requires extra supervision by an additional person for safety. The result highlights that new relatively low-cost video see-through displays may provide new options to enhance spatial judgments and build trust for VR users. Moreover, analysis of our collected data indicates that increased PEBW is associated with faster walking velocities, larger steps, and fewer turns, likely reflecting boosted confidence and comfort during PEBW in the pre-experiment procedure and direct blind walk for the experiment.

### 6.1.1 Limitations and Future Work

While our work provides a comprehensive study regarding pre-experiment procedures in VR using the direct blind walking method, further research is needed to understand these effects in other contexts. Additional investigation on the relationship between pre-experiment conditions and real-world distance judgment studies would be beneficial. Examining the influence of PEBW on alternative measurement techniques like verbal reporting, blind throwing, and triangulated walking could offer a more complete perspective. Moreover, extending this research into augmented reality settings and analyzing the impact of pre-experiment protocols would be an intriguing direction, especially using see-through mode, given the potential for increased user confidence when visualizing the real environment in AR. This continued investigation across different settings and techniques can build on the foundation established here. It will provide broader insights into how prior experience impacts perceived distances. Pursuing such open avenues will lead to increased theoretical and practical knowledge about the complex factors shaping spatial judgments.

Furthermore, the blind walking with feedback approach warrants deeper exploration and research, given its significant influence on enhancing distance perception in applications. This method is crucial for facilitating rapid adaptation and familiarization, essential components of effective training in virtual environments using HMDs.

### 6.1.2 Takeaway messages for researchers and VR developers

Our takeaway and suggestions for researchers and VR developers are to make sure to include a well-reported pre-experimental procedure. This includes if experiments use PEBW or any pre-experiment walk and their durations. Additionally, reporting the details of the place for doing the PBEW procedure, such as width and length, can help compare various studies' results with each other. Most researchers do 3 to 5 minutes of PEBW. However, we found accurate performance can be reached with approximately 10 to 15 minutes of PEBW. In some scenarios and applications, if it's not possible to run PEBW due to issues such as not having enough time or an experimenter to control the experiment for the PEBW task, we suggest doing video See-Through mode walking using modern HMDs such as Meta Quest-Pro that utilizes color camera video see-through.

## 6.2 Overall Summary

In summary, the experiments conducted in this thesis demonstrate that the amount of PEBW significantly influences participants' distance judgments in VR when using the direct blind walking method. Both insufficient and excessive PEBW were shown to distort judged distance, causing underestimation and overestimation, respectively. These results emphasize the importance of documenting PEBW procedures precisely, including details like duration and walking area size, to qualify appropriate interpretation and comparison of studies. Additionally, this work shows how such a pre-experiment procedure with different durations can impact participants' perceived distance in VR.

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