THE EFFECT OF PRIOR VIRTUAL REALITY EXPERIENCE ON LOCOMOTION AND NAVIGATION IN VIRTUAL ENVIRONMENTS

A PhD Dissertation Proposal
Presented to
the Graduate School of
Clemson University

In Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy
Human-Centered Computing

---

by
Moloud Nasiri
December 2023

Accepted by:
Dr. Andrew Robb, Committee Chair
Dr. Brygg Ullmer,
Dr. Guo Freeman,
and Dr. Larry Hodges

Abstract

Virtual Reality (VR) is becoming more accessible and widely utilized in crucial disciplines like training, communication, health care, and education. One of the important parts of VR applications is walking through virtual environments. So, researchers have broadly studied various kinds of walking in VR as it can reduce sickness, improve the sense of presence, and enhance the general user experience. Due to the recent availability of consumer Head Mounted Displays(HMDs), people are using HMDs in all sorts of different locations. It underscores the need for locomotion methods that allow users to move through large Immersive Virtual Environments (IVEs) when occupying a small physical space or even seated.

Although many aspects of locomotion in VR have received extensive research, very little work has considered how locomotive behaviors might change over time as users become more experienced in IVEs. As HMDs were rarely encountered outside of a lab before 2016, most locomotion research before this was likely conducted with VR novices who had no prior experience with the technology. However, as this is no longer the case, it is important to consider whether locomotive behaviors may evolve over time with user experience. This proposal specifically studies locomotive behaviors and effects that may adjust over time.

For the first study, we conducted experiments measuring novice and experienced subjects' gait parameters in VR and real environments. Prior research has established that users' gait in virtual and real environments differs; however, little research has evaluated how users' gait differs as users gain more experience with VR. We conducted experiments measuring novice and experienced subjects' gait parameters in VR and real environments. Results showed that subjects' performance in VR and Real World was more similar in the last trials than in the first trials; their walking dissimilarity in the start trials diminished by walking more trials. We found the trial as a significant variable affecting the walking speed, step length, and trunk angle for both groups of users. While the main effect of expertise was not observed, an interaction effect between expertise and the trial number was shown. The trunk angle increased over time for novices but decreased for experts.

The second study reports the results of an experiment investigating how users' behavior with two locomotion methods changed over four weeks: teleportation and joystick-based locomotion. Twenty novice VR users (no more than 1 hour prior experience with any form of walking in VR) were recruited. They loaned an Oculus Quest for four weeks on their own time, including an activity we provided them with. Results showed that the time required to complete the navigation task decreased faster for joystick-based locomotion. Spatial memory improved with time, particularly when using teleportation (which starts disadvantaged to joystick-based locomotion). Also, overall cybersickness decreased slightly over time; two dimensions of cybersickness (nausea and disorientation) increased notably over time using joystick-based navigation.

The next study presents the findings of a longitudinal research study investigating the effects of locomotion methods within virtual reality on participants' spatial awareness during VR experiences and subsequent real-world gait parameters. The study encompasses two distinct environments: the real world and VR. In the real world setting, we analyze key gait parameters, including walking speed, distance traveled, and step count, both pre and post-VR exposure, to perceive the influence of VR locomotion on post-VR gait behavior. Additionally, we assess participants' spatial awareness and the occurrence of simulator sickness, considering two locomotion methods: joystick and teleportation. Our results reveal significant changes in gait parameters associated with increased VR locomotion experience. Furthermore, we observe a remarkable reduction in cybersickness symptoms over successive VR sessions, particularly evident among participants utilizing joystick locomotion. This study contributes to the understanding of gait behavior influenced by VR locomotion technology and the duration of VR immersion.

Together, these studies inform how locomotion and navigation behavior may change in VR as users become more accustomed to walking in virtual reality settings. Also, comparative studies on locomotion methods help VR developers to implement the better-suited locomotion method. Thus, it provides knowledge to design and develop VR systems to perform better for different applications and groups of users.

Acknowledgments

Completing a Ph.D. is a monumental achievement, and I still find it hard to believe I have reached this milestone. I want to raise a toast to everyone who has been a part of this incredible journey with me.

First and foremost, I extend my deepest appreciation to Dr. Andrew Robb, whose invaluable support has been fundamental to my achievements over these past four years. It has been an extraordinary privilege to benefit from the guidance and mentorship of such an esteemed academic. I also express my profound gratitude to Dr. Larry Hodges for his exceptional leadership and dedication to the Virtual Environments Group lab. His expertise and guidance have been crucial in shaping my academic journey and personal growth. Special thanks go to the faculty and staff at the School of Computing. Their collective wisdom, support, and encouragement have been instrumental in my academic development and creating an environment conducive to learning and innovation.

Additionally, heartfelt thanks go to my friends and family for their unwavering support and encouragement throughout this journey. Their persistent belief in me has been a continual source of strength and inspiration.

To each of you, thank you for being an integral part of this life-changing experience.

Table of Contents

List of Tables

List of Figures

Chapter 1

Introduction

Virtual Reality (VR) has emerged as a transformative technology, revolutionizing various sectors such as healthcare, education, communications, and entertainment. Different aspects of VR that influence VR sickness, enhance the sense of presence, and improve the overall user experience have been the subject of extensive research [10, 44, 107, 120]. One of the key aspects of VR applications that have garnered significant attention is locomotion, which allows users to navigate through immersive virtual environments (VEs). This feature is crucial in a multitude of applications, from rehabilitation in healthcare to immersive gaming experiences [58, 84].

The concept of locomotion in VR is not new, but recent advancements in technology have ushered in a new era for VR locomotion. The latest technical and interaction advancements have sparked interest among researchers and users alike, leading to a surge in the analysis and experience of current VR locomotion techniques [10]. Locomotion in VR is more than just a means of movement; it is a fundamental part of the VR experience. It is the mechanism that allows users to interact with the virtual world, explore it, and engage with it. It is what makes the virtual world feel real and immersive. However, achieving effective locomotion in VR is a complex task. It requires careful consideration of various factors, including the size and shape of the room, the surrounding objects in the virtual and real worlds, and the user's physical capabilities and comfort [107].

Different methods of locomotion have been developed to cater to these factors. These methods range from real walking, where users physically walk in the real world to move in the virtual world, to more abstract methods such as walking-in-place, teleportation, and joystick-based locomotion [10, 44, 120]. Each method has its advantages and disadvantages, and the choice of method can significantly impact the user's experience in VR.

Real walking, for instance, offers a high level of immersion and presence, making it an ideal method for VR applications. However, it requires a large physical space, which may not always be available. Walking-in-place and joystick-based locomotion, on the other hand, are more accessible methods that can be used in smaller spaces. However, they can also increase disorientation and reduce a user's sense of presence within a VR environment [44, 120].

Teleportation is another commonly used method of locomotion in VR. It allows users to move instantly from one location to another, making it a convenient method for navigating large virtual environments. However, like walking-in-place and joystick-based locomotion, teleportation can also increase disorientation and reduce a user's sense of presence [10].

Locomotion in VR is intrinsically tied to navigation, as the way users move directly impacts how they explore and interact with the virtual environment. The ability to navigate effectively in VR is not only a function of the locomotion technique used but also of the user's understanding of the virtual space. This coupling of locomotion and navigation is a critical aspect of VR design, as it can significantly influence the user's sense of presence, spatial understanding, and overall VR experience [31, 92]. Therefore, research into VR locomotion must also consider its impact on navigation, as the two are inextricably linked in the context of immersive VR experiences.

1.1 Real Walking in VR

Real walking in VR, despite its inherent challenges, offers unique advantages over other locomotion methods in terms of immersion, presence, spatial understanding, and the ability to mimic real-world walking dynamics. Its applications in various fields highlight its importance in the realm of VR locomotion.

In the fields of navigation and spatial cognition, real walking in VR has been shown to have significant implications as compared to other locomotion methods such as teleportation or joystick-based locomotion [92, 112]. This is likely due to the naturalistic interaction with the environment that real walking affords, which can lead to a more accurate mental representation of the virtual space [92]. Maneuvrier et al. found that a higher sense of presence in VR, which is often associated with real walking, promoted better performance on a virtual spatial cognition evaluation [69]. This suggests that real walking in VR, with its naturalistic movement dynamics, could provide a more accurate representation of distances in VR, which could be beneficial in applications where accurate spatial cognition is crucial, such as navigation training. Another study by Mahmud et al. found that auditory feedback could improve gait performance in VR, making walking in VR more accessible for people with and without mobility impairments [68]. This suggests that multi-modal feedback, which is naturally present in real walking, could enhance navigation and spatial understanding in VR.

In contrast, a study by Larrue et al. compared the impact of motor activity on spatial cognition in VR by comparing a walking interface with a brain-computer interface (BCI) that enabled navigation without any motor activity. Surprisingly, they found similar performances across both interfaces, suggesting that motor activity, such as real walking, is not essential for learning and transferring spatial knowledge in VR [63]. However, this does not diminish the potential benefits of real walking in VR, especially in terms of immersion and presence.

Finally, in a more recent study, Kafri et al. compared the performance of young and older adults in a complex task while navigating in a real shopping mall and a high-fidelity virtual replica of the mall. They found that both age groups walked faster with higher step lengths and lower gait variability in the real-world environment compared to the virtual environment. However, the younger group performed better in terms of task completion time and score in both environments [54]. This study underscores the potential differences in gait and task performance between real and virtual environments, which could have implications for the design of VR applications that aim to mimic real-world walking dynamics.

1.2 Is Gait Affected by Prior Experience Walking in VR?

Just as age can influence locomotion and navigation in both real and virtual environments, it may be that a user's gait in VR will change over time as they spend more time walking in VR. As users gain more familiarity with VR, their gait within the virtual environment may evolve, potentially becoming more similar to their real-world gait. This hypothesis is supported by research in other domains, which has shown that experience can significantly influence behavior and performance in virtual environments [28].

However, despite the potential implications of such changes, there is a surprising lack of research exploring how gait in VR changes over time as users gain more experience with VR. This gap in the literature is significant, given the potential impact of such changes on various applications, from rehabilitation and training to user comfort and game design.

For instance, in the context of rehabilitation, understanding how gait evolves over time in VR could inform the design of more effective rehabilitation protocols. A study by de Rooij et al. [34] found that virtual reality gait training was not statistically different from non-virtual reality gait training in improving participation in community-living people after stroke. However, the study did not consider the potential impact of users' prior experience with VR on their gait and performance. If gait does indeed change over time as users gain more experience in VR, this could have significant implications for the effectiveness of VR-based rehabilitation protocols.

Similarly, understanding how gait changes over time in VR could help design more effective training programs in the context of VR-based training and education. For instance, if gait in VR becomes more similar to real-world gait as users gain more experience in VR, this could potentially improve the transfer of skills learned in VR to the real world. This is supported by a study by Cooper et al. [28], which found that VR training with augmented, task-relevant, multisensory cues resulted in higher objective performance during a real-world task.

Furthermore, changes in gait over time in VR could also have implications for user comfort and the prevention of VR sickness. If users adjust their gait in VR to reduce discomfort and VR sickness as they gain more experience, this could potentially improve the overall user experience in VR. This is supported by a study by Al-Amri et al. [1], which found that self-paced treadmill walking in VR was a safe and well-tolerated intervention that users positively rated.

Finally, changes in gait over time in VR could also have implications for social VR applications and VR game design. In social VR applications, where users' avatars mimic their real-world movements, changes in gait could affect how users perceive and interact with each other. In VR games, understanding how gait changes over time could inform the design of game mechanics, levels, and challenges to accommodate these changes and maintain an engaging and immersive experience.

Given these potential implications, it is crucial to conduct longitudinal research exploring how gait may change over time as users become more accustomed to walking in VR. Such research could provide valuable insights into the evolution of gait in VR, the factors influencing this evolution, and the potential applications of these insights in various fields. This dissertation represents the first step towards understanding how gait in VR may change over time as users spend more time using and walking in VR.

1.3 Examining Gait in Virtual Reality and the Real World

Gait in virtual reality and in the real world can indeed exhibit dissimilar characteristics due to the unique environmental and perceptual factors inherent in each setting. When individuals navigate VR, they encounter a computer-generated simulated environment that may differ substantially from their physical surroundings. Consequently, participants may display gait alterations in VR to adapt to the novel visual cues and virtual terrain, which can deviate from real-world conditions.

An important technique that can be used to understand gait in VR is to compare virtual walking to walking in the real world. Any differences between real walking and walking in VR can provide important insights into VR systems' potential limitations or advantages in replicating real-world locomotion. Prior studies were conducted to understand users' gait behaviors in Virtual Environments (VE) compared to the real environment (RE). Several experiments were completed in two real and virtual world states when participants were asked to walk in both.

Hollman et al. demonstrated considerable differences in gait parameters such as stride length, stride velocity, and step width when users walked in VE compared to RE. Subjects walked in the VR environment with reduced stride lengths, increased step widths, and increased variability in stride velocity [48]. Likewise, Mohler et al. ran experiments where participants wore a Head-Mounted Display (HMD) and a backpack. They had a shorter stride length, slower walking velocity, and a lower head-trunk angle in VE than when walking in the real world [74].

The virtual environment's limited physical space and reduced sensory feedback further contribute to modifications in gait patterns, as individuals may navigate within confined areas and experience a partial absence of real-world feedback that normally influences their walking style in reality. Additionally, simulator sickness in VR can introduce discomfort and disorientation, potentially affecting gait behaviors as users strive to accommodate the unfamiliar sensations.

Despite these disparities, some similarities between gait in VR and the real world can emerge under certain circumstances. VR systems that closely replicate real-world scenarios or employ advanced tracking technologies seek to minimize the divergence in gait patterns. Moreover, individuals with prior experience in VR locomotion may adapt more readily, showcasing gait patterns that align better with their real-world counterparts. Studying these differences and similarities in gait between VR and the real world is crucial to optimizing VR experiences for users, ensuring safe and comfortable navigation within virtual environments.

Unlike the work above, Canessa et al. found no significant differences between gait in VE and RE, including total distance, stride length, and step length. However, they observed differences in other gait parameters, such as peak swing velocity, step count, and cadence, which they also explained by wearing cabled HMD for the virtual conditions [19]. Understanding these distinctions can guide the development of effective VR locomotion techniques and promote a seamless integration between virtual and real-world locomotion practices, fostering immersive and engaging virtual experiences with potential applications in various domains such as training, rehabilitation, and entertainment.

1.4 Contributions

This dissertation investigates the relationship between gait, navigation, and prior experience with virtual reality. It consists of three studies that examine different aspects of this intersection:

1. A study comparing the gait of inexperienced and experienced VR users in the real world and virtual reality.
2. A study examining navigation behaviors and spatial understanding over time using joystick-based locomotion and teleportation.
3. A study exploring how gait in the real world changes after navigating in a virtual environment and how this effect is moderated by experience with VR.

1.4.1 Study 1

Chapter 3 presents the design and results of the first study. The first study presented in Chapter 3 highlights the need to consider users' expertise in VEs when designing walking assets and to analyze their effectiveness. Most of the experimental studies on locomotion aids available in the literature do not distinguish between experienced and inexperienced users. However, locomotion assets appropriate for experienced users may need more practical support for inexperienced users.

We recruited two groups of participants: participants with little to no experience in VR (referred to as novices) and participants with substantial prior experience in VR (referred to as experts). Participants walked controlled in real and corresponding virtual conditions to record their gait proportions. Each participant's difference in gait parameters was computed and analyzed to determine whether walking in VE and RE varied between novice and expert users. This proposal presents the results of two completed studies and describes the next research study in progress.

So, the main contributions of this study are:

1. Evaluating the differences between walking in the real world and IVEs.
2. Examining the effect of prior experience to moderate the gait differences in real and VR environments.

1.4.2 Study 2

Chapter 4 introduces the design and findings of the second study. This longitudinal experiment involved participants engaging in a navigation activity four times over a four-week duration. Prior to commencing the experiment, participants were randomly assigned to one of two between-subject conditions: 1) utilizing teleportation for locomotion or 2) employing joystick-based locomotion. Each time they performed the activity, participants underwent ten navigation trials, during which their completion time and accuracy with a spatial updating task were recorded. Additionally, participants completed the Simulator Sickness Questionnaire [57] and the iGroup presence questionnaire [94].

Our hypothesis posits that changes in participants' locomotive performance are linked to the locomotion technique they use in VR. Furthermore, we anticipated observing the effect of time/experience on participants' performance in locomotion and navigation within the immersive virtual environment (IVE). The main contributions of this research are as follows:

1. Evaluating users' locomotive behaviors alters across sessions as they become more familiar with VR
2. Evaluating different patterns of change between locomotion methods
3. Evaluating the effects of the locomotion method on simulator sickness and presence over time?

1.4.3 Study 3

Chapter 5 presents the design and results of the third study. As a continuation of prior research, this study delved into potential changes in locomotion and navigation in VR, as well as their lasting effects over a three-session period. Our hypothesis was that both navigation parameters, like spatial memory, and locomotion parameters, such as walking speed in the real world, would be altered after multiple VR sessions. The main objective was to investigate how VR locomotion and navigation, using both joystick and teleportation techniques, would modify participants' walking behavior in both VR and the real world over time.

To investigate the effects of walking in immersive virtual environments (IVEs) on novice VR users' walking behavior, a controlled experiment was conducted. Firstly, participants completed 20 trials of natural walking in a real room, during which their gait parameters were measured. Subsequently, participants used either the joystick-based or teleportation technique to navigate through a virtual maze-like setting (see Figure 5.2). Ten navigation trials were conducted, during which parameters such as completion time and spatial accuracy were recorded. Finally, participants completed another 20 trials of natural walking in the real world to assess their walking behavior after the VR experience. The second real-world situation was identical to the first one to ensure result reliability.

So, the main contributions of this study are:

1. Evaluating participants' real-world locomotive behaviors after experiencing VR locomotion
2. Evaluating locomotion method impact on gait parameters in the real world
3. Evaluating participants' VR locomotive behaviors over time

Chapter 2

Related Works

2.1 Locomotion Techniques

Determining an effective method for moving players within virtual environments has become a crucial challenge and has led to renewed interest in the study of locomotion techniques in virtual environments. Virtual reality locomotion allows users to move within an infinite-scale virtual world while remaining confined to a room-scale real-world environment [46]. Locomotion is a basic form of human-computer interaction, and in virtual reality, it significantly impacts aspects of the user experience, such as enjoyment, frustration, fatigue, motion sickness, and presence. When the virtual environment is the same size as the physical environment, and the system allows for natural movement, users can walk to control the virtual-world locomotion. However, when the virtual environment is larger than the physical environment, alternative methods of locomotion must be used. As a result, new techniques have emerged, but choosing which technique to use needs to be better understood, developed, or experimented with [24].

VR locomotion is an essential interaction element that facilitates navigation in VR environments [17, 45]. This locomotion can, however, lead to simulator sickness [38, 117] and disorientation [15]. Finding an efficient Locomotion Technique (LT) that does not negatively impact presence, cause motion sickness, or induce fatigue is a significant challenge currently the focus of many research studies [13]. Numerous novel LTs have been introduced with the rising popularity of VR [11], leading to a greater pool of LTs. It requires researchers, developers, and designers to get an overview of existing LTs to know all possible choices among LTs, identify gaps, or design a novel LT.

Since the early days of VR development, different locomotion techniques have been designed and analyzed to make efficient, user-friendly navigation in virtual environments [11]. The literature review established the diverse character of the different VR locomotion techniques under comparative settings. A study of locomotion techniques revealed three main categories: those that focus on the user's body, those that focus on external peripherals, and those that use a combination of both. Each of these categories can be divided into various subcategories [24].

Joystick locomotion employing artificial interaction allows for a less physically intense experience, with the user being stationary and simply using a controller; however, it can be cognitively intense and lead more easily to VR sickness [37]. Teleportation effortlessly takes the users from place to place, though the visual jumps may ruin the immersion and spatial orientation [12]. A teleportation technique named ”Dash” tries to lessen spatial disorientation by supplying a small quantity of optical flow during the viewpoint change to enable path integration [7]. Dash facilitates path integration and decreases spatial disorientation compared to standard teleportation while reducing VR sickness.

Janeh et al. indicated significant distinctions in biomechanical gait parameters, such as step length and walking velocity in virtual and real environments for younger and older adults. The results showed that, unlike younger adults, the older adults walked at a comparable speed in real and virtual environments. Also, older adults had similar step lengths in the VE and the real world, whereas younger adults had a significantly shorter step length in the VE than in the real world [52]

Langbehn et al. compared joystick, teleportation, and redirected walking. Their results showed that travel time was the shortest for teleportation, and the joystick had the highest VR sickness. Also, no difference has been found in presence scores between the three locomotion methods, but teleportation and redirected walking were most preferred [62]. In addition, comparing teleportation to three virtual locomotion techniques, including the joystick method, joystick with tunneling (with a restricted field of view), and body tilt, showed no difference in presence. However, the quality of the experience was significantly higher for teleportation [114].

Coomer et al. examined four locomotion methods: arm cycling, joystick, teleportation, and point-tugging (users select a point in space and pull themselves toward it by pushing on a button on a controller). They found that teleportation and arm-cycling had lower simulator sickness than joystick and point-tugging. Also, users walked further by teleportation than the other three methods. Moreover, teleportation caused more spatial disorientation than others, so they looked around more [27].

In conclusion, the study of locomotion techniques in virtual environments is crucial for enabling effective player movement. Researchers have explored various approaches, considering physical intensity, cognitive demands, spatial orientation, and presence. Evaluating different locomotion methods has revealed distinctions in user preferences, simulator sickness, presence, and the overall quality of the experience. Continued research in this field aims to enhance the user's locomotion experience in virtual environments while mitigating negative effects such as motion sickness and disorientation.

2.2 VR Experience

Previous experience with virtual reality can affect a user's perception and actions in VR in several ways. For example, individuals with prior experience may easily adapt to the immersive environment and better understand how to interact. They may also have a better sense of depth perception and spatial awareness, which can help them navigate virtual environments more effectively. On the other hand, individuals with limited prior experience may have a harder time adjusting to the VR environment. They may experience disorientation, motion sickness, and difficulty interacting with virtual objects. They may also struggle with spatial awareness and depth perception, making it difficult to navigate the virtual environment. Additionally, prior experience can shape users' expectations and how they react to different virtual scenarios. For instance, users with experience in simulation, gaming, or training in virtual reality might react differently than users who have never been exposed to it.

Unfortunately, most experimental analyses on navigation assets do not differentiate between experienced and inexperienced users. Navigation assets suitable for experienced users may not provide a proper level of support for inexperienced users. So, resolutions enhancing inexperienced users' navigation performance may not benefit experienced users [18].

Lin et al. analyzed the effect of repeated exposures to indoor environments on people's indoor wayfinding performance under normal conditions and during a fire emergency, which could cause mental stress. Indoor wayfinding experiments were performed in an immersive virtual museum. Collected data included participants' wayfinding performance, sense of direction, wayfinding anxiety, and simulator sickness. The results indicated a significant positive effect of repeated exposure on participants' wayfinding performance, which decreased the time needed to complete the required task [65].

Burigut et al. ran an experimental study whose purpose was: (1) to compare three navigation assets that allow users to perform wayfinding tasks in virtual desktop environments by pointing out the location of objects or places; (2) to evaluate the impacts of user experience with 3D desktop VEs on the navigation assets efficacy. They compared the navigation performance (whole time to conducting a search task) of 48 subjects separated into two groups of experienced and inexperienced VR users. Based on their results, differences are strongly influenced by the virtual environment where navigation takes place, like abstract vs. geographic environments [18].

Since the modern 3D computer game is one of the most common virtual environments or 3D interfaces, using computer games as the basis for virtual environment evolution would be helpful [110]. The present era of computer games gives the experience of virtual worlds featuring user-friendly interaction and the simulation of the real world. Frey et al. studied the effects of game experience on psychological experimenting in IVEs, considering if training could lower the performance distinctions between users who play games and users who do not [41].

Moreover, another research project has explained the impacts of gaming experience on virtual environment evaluations involving navigation tasks. Results revealed that perceived gaming skill and progress in a first-person-shooter (FPS) game were the most compatible metrics demonstrating significant correlations with performance in time-based navigation tasks [103]. Beilinson et al. conducted longitudinal research, tracking users over 45-minute sessions when interacting with each other in VR; evaluating results showed that the feeling of presence did not change over time [4].

Likewise, [84] is a longitudinal study investigating how users played Minecraft on the desktop and in VR, including three 45-minute sessions on each setup. However, no effects were perceived within this time frame. Moreover, participants adapted to the VE and visual perturbations over time based on the results indicating increasing stride length and reducing stride width and time [70].

Richardson et al. studied the relationship between prior video game experience and spatial performance in virtual and real environments. Across two experiments, the gaming experience was associated with performance in virtual desktop environments; those with more video game experience pointed more accurately to non-visible targets [89]. The results suggest that the gaming experience is related to the ability to make precise spatial representations while moving in Immersive Virtual Environment.

The study's results by Murias et al. confirmed that individuals who have played video games for longer perform better on a virtual-navigation task. However, this effect was most pronounced in players of video games that involve navigation, and it cannot be solely attributed to their mastery of game controls. Additionally, participants who frequently play video games involving navigation reported employing more efficient navigation strategies, such as utilizing cognitive maps or relying on learned routes. These findings support the idea that improved navigation and orientation skills in video game players are likely a result of regular practice of these skills for entertainment purposes [78]. Although, there is yet a significant lack of research on the expected time users need to become proficient at traveling in the VR world.

Previous experience with virtual reality can significantly influence a user's perception and actions within VR environments. Those with prior experience tend to adapt more easily, possess better depth perception and spatial awareness, and navigate virtual environments more effectively. Conversely, individuals with limited experience may struggle with adjusting to the VR environment, experiencing disorientation and difficulty interacting with virtual objects. Moreover, prior experience shapes users' expectations and reactions to virtual scenarios. However, the differentiation between experienced and inexperienced users is often overlooked in experimental analyses on navigation assets, leading to a need for proper support for inexperienced users. Nevertheless, studies have shown the positive impact of repeated exposure on wayfinding performance and the potential benefits of using computer games as a basis for virtual environment development. The gaming experience has been linked to improved performance in virtual environments, particularly in navigation tasks and efficient navigation strategies. It is important to explore further the expected time required for users to become proficient in navigating the VR world. Overall, understanding the role of prior experience and its implications can enhance the design and effectiveness of virtual reality experiences.

2.3 Navigation and Spatial Memory

Navigation includes wayfinding and traveling, which are closely affiliated and used. So, travel technique may affect the ability to perform wayfinding tasks and the user's spatial orientation [14]. One common VR navigation approach is using a joystick or other handheld controller to move through the virtual environment. This approach has the advantage of being intuitive and easy to use, but it can also lead to feelings of disorientation or motion sickness in some users. Another approach uses body movements, such as walking or head movements, to navigate the virtual environment. This approach is often called ”natural navigation” and is considered more immersive and less likely to cause disorientation or motion sickness [27]. However, it can be more difficult to implement and require specialized hardware such as motion capture systems.

The memory system encodes, stores, recognizes, embodies, and recalls spatial information about the environment is called spatial memory [67]. Spatial memory is responsible for encoding, storing, and retrieving information about an individual's spatial environment, including location, orientation, and relationships among objects [2, 3]. It enables us to navigate and locate objects in our environment. It is critical for tasks such as finding one's way around a new city, remembering where items are stored in a room, or remembering the layout of a building. Studies have shown that the hippocampus and surrounding brain regions are key structures involved in spatial memory [77]. A classic study in spatial memory is O'Keefe and Nadel's publication ”The Hippocampus as a Cognitive Map.” In this study, they proposed the idea of a cognitive map which refers to a mental representation of the environment that allows for the storage and retrieval of spatial information [82].

Navigation and spatial memory in virtual reality are closely related [75]. The level of realism and presence in the virtual environment and interaction and exploration can impact spatial memory recall. Navigation in virtual reality can improve spatial memory recall, as individuals can actively explore and interact with the virtual environment. The level of realism and presence in the virtual environment has been shown to impact spatial memory recall positively [61]. Research in cognitive psychology has shown that recall is superior in the same environment in which the learning took place [42]. The representation of space in virtual reality can also impact spatial memory, with more realistic and dynamic virtual environments leading to better memory recall [83].

Previous research on virtual reality navigation has focused on developing methods to help users navigate and explore virtual environments intuitively and efficiently. This has included studying spatial cues, such as landmarks and environmental features, to allow users to orient themselves and understand their location within a virtual environment [96]. Researchers have also studied navigation aids, such as maps and compasses, and the impact of different forms of movement (e.g., walking vs. teleportation) on navigation performance and user experience. Another area of research has been on how virtual reality can assist with real-world navigation tasks, such as wayfinding, for people with visual impairments [53].

One area of research has focused on the design of virtual environments, specifically the creation of virtual worlds that are large and complex enough to support effective navigation while also being intuitive and easy to use [30]. Researchers have also investigated using different input devices, such as a joystick, keyboard, and mouse, and more advanced devices, such as the Oculus Touch and the Vive controllers. Some research studied the impact of navigation in VR on user performance, the occurrence of cybersickness symptoms, and the level of presence [22]. Studies have shown that VR navigation can significantly impact a user's sense of presence and spatial awareness, which can affect a user's ability to navigate and interact with virtual environments.

Xu et al. examined the effect of three locomotion techniques (joystick, pointing-and-teleporting, and walking-in-place) on object location learning and recall. Participants were asked to memorize the location of a virtual object in a virtual environment (VE). Unexpectedly, results indicated that the average placement error, the distance between the original and recalled object location, was approximately the same for all locomotion techniques [121]. Overall, the research on Navigation in Virtual Reality continues to evolve as the technology develops, and new ways of interacting with virtual environments are being explored.

In closing, navigation and spatial memory are crucial in virtual reality experiences. The choice of navigation technique, such as joystick-based or natural navigation, can impact users' sense of disorientation or immersion. Spatial memory, responsible for encoding and retrieving spatial information, is closely linked to navigation in virtual reality. The level of realism and presence in virtual environments can enhance spatial memory recall. Researchers have explored various methods to improve navigation, including using spatial cues, navigation aids, and the design of large and intuitive virtual worlds. Additionally, investigations have been conducted on the impact of different input devices, user performance, cybersickness symptoms, and presence in virtual reality navigation. While there is ongoing research in this field, it is clear that navigation in virtual reality continues to evolve with advancements in technology and innovative approaches to interacting with virtual environments.

2.4 VR Afteraffects

Walking in virtual reality (VR) has become a popular way to experience immersive environments and explore new environments without physical limitations. However, the effects of walking in VR can extend beyond the virtual environment and may cause aftereffects that persist into the real world. Aftereffects refer to changes in perception or behavior after exposure to a stimulus. The impact of VR locomotion on real-world behavior may be influenced by various factors, including the type of virtual environment [101], the duration of exposure [106], and the user's prior experience with VR [79].

Several research efforts have examined how VR locomotion affects posture control and balance. Chen et al. explored the short-term impact of VR training on balance. They compared it to other active interventions, such as traditional balance training, sensory integration balance training, neurodevelopment treatment, and cycling, for individuals with Parkinson's disease [23]. The results showed promising moderate evidence for the effectiveness of VR in improving balance in these individuals. While the impact was insufficient to reach the clinical significance threshold, VR was just as effective as active interventions and could be considered a supplementary therapy for balance rehabilitation in Parkinson's patients. Another study by De Rooij et al. shows a significant impact of VR walking on patients' balance and gait ability after stroke. They studied if VR training for balance or gait training is effective for patients with stroke and found out it helps improve their balance or gait ability [33].

In addition to postural control and balance, VR locomotion has also impacted spatial perception and body ownership. Embodied virtual bodies in VR significantly affect the perception of the self-body, for example, in aspects like perceived size, shape, posture, location, or sense of ownership [72]. Reinhard et al. studied how the age of an avatar affects a person's walking speed after embodiment, taking into account the role of body ownership and spatial presence. The results showed that participants who embodied older avatars took more time walking a specific distance than those who embodied young avatars [88].

Studies have revealed that walking in virtual reality can cause changes in perception of size, depth, and motion, leading to difficulties in adapting to the real world. One study found that walking experience in a virtual environment can impact an individual's subsequent distance estimates in the physical world [116]. Another survey by Maruhn et al. compared various methods for measuring depth perception in VR during active locomotion and found that there were varying levels of exposure for different ways and a predicted impact of translation gains [71]. Varmaghani et al. investigated if exposure to VR can lead to a decline in cognitive spatial ability and attention and if this decline is related to cybersickness [113].

As kinematic measurements indicate, VR can cause postural instability while standing or walking. The deviations in gait patterns suggest that walking in a VR environment can cause gait instability in healthy individuals. It is likely due to the compensatory response to visual stimulation in the VR environment [47]. Further study is necessary to fully comprehend the impact of VR locomotion on real-world behavior and establish guidelines for the safe and effective use of VR for movement. When considering the effects of VR, it is important to weigh the potential risks and benefits for different applications, such as therapy and rehabilitation, entertainment, and education.

Studying the aftereffects of walking in virtual reality (VR) on real-world walking can have several potential benefits to society, like improved rehabilitation. Virtual reality is increasingly used in rehabilitation settings to help people regain their walking ability after an injury or illness [8]. By studying the aftereffects of walking in VR on real-world walking, researchers can better understand how to use VR to improve rehabilitation outcomes. It helps to provide safer mobility for older adults; as the global population ages, interventions are needed to help them maintain mobility and independence [20]. By studying the aftereffects of walking in VR on real-world walking, researchers can develop safer and more effective interventions for older adults.

In summary, the effects of walking in virtual reality extend beyond the virtual environment and can impact real-world behavior. Factors such as the type of virtual environment, duration of exposure, and prior VR experience can influence the impact of VR locomotion on posture control, balance, spatial perception, and body ownership. Studies have shown promising evidence of the effectiveness of VR in improving balance in individuals with Parkinson's disease and stroke patients. However, walking in VR can also lead to difficulties adapting to the real world, affecting distance estimation, depth perception, cognitive spatial ability, and gait patterns. Further research is needed to fully understand the implications of VR locomotion on real-world behavior and establish guidelines for its safe and effective use. By studying the aftereffects of walking in VR on real-world walking, we can enhance rehabilitation, gain insights into cognitive processes, promote safer mobility for older adults, improve athletic training, and deepen our understanding of the brain's functioning.

2.5 Presence

Virtual reality is an advanced human-computer interface that incorporates various sensory modalities, such as visual, haptic, and auditory cues, to enhance the realism and immersion of the virtual environment [97]. This heightened sense of realism gives rise to a phenomenon called ”presence,” which denotes the user's subjective feeling of truly existing within the virtual world, facilitated by computer-generated visual and auditory stimuli [5, 99]. By offering highly realistic and immersive experiences, VR emerges as a potent tool capable of enabling the creation of unique and innovative consumption experiences [32, 64].

The concept of presence is widely used to measure the immersive capacity of interactive experiences in virtual environments [99]. It is referred to by experts in various ways, such as telepresence, which creates a sense of ”being there,” and social presence, which focuses on the feeling of ”being there with another” and examines interactions between real and virtual humans [9]. For this study, we adopt the definition of presence that involves the transportation of the user's consciousness to the virtual environment [66]. Our experimentations do not include interactions with human-like characters, so social presence is irrelevant.

We focus on a subtype of presence that closely aligns with its original concept, ”Spatial Presence.” Spatial Presence is commonly described as ”a sense of being there,” where a person's perception fails to accurately acknowledge the technology that creates the illusion of being in a different physical location and environment from their actual surroundings in the real world. Although this definition is similar to the earlier notion of ”telepresence” [35], the term ”telepresence” is more general as it is not specific to particular media technologies, such as virtual reality, often associated with it.

Academic research in this area explores the psychological and cognitive mechanisms that underlie spatial presence, the potential applications of spatial presence in various fields (e.g., education, training, therapy, entertainment), and the design principles to enhance and optimize the feeling of presence in mixed reality experiences. Researchers use various methodologies to study spatial presence, such as surveys, questionnaires, physiological measurements, and qualitative interviews to understand how users perceive and experience mixed realities [43]. The insights gained from these studies can inform the development of better mixed-reality systems and applications that provide users with more immersive and engaging experiences.

The primary characteristic of spatial presence is the belief in being present in a mediated environment. This quality makes spatial presence a critical factor in various communication applications. For instance: The success of simulation-based learning relies on the learner's sense of being in the simulated environment [87]. Furthermore, spatial presence can enhance existing media effects, such as The enjoyment of using entertainment media, like video games [109]. Coordinated action in organizations, where members' feeling of presence in shared virtual spaces, facilitated by videoconferencing and other communication tools, improves collaboration [39].

Several factors contribute to the perception of presence in virtual reality, including the level of immersion provided by the technology, the quality of sensory inputs (such as visual, auditory, and tactile cues) [100], the user's ability to interact with virtual elements, and the coherence and relevance of the virtual content to the real-world context [90]. By integrating certain aspects, it is possible to expect a substantial improvement in the user's feeling of presence. Features involve utilizing faster processors with higher update rates, more precise tracking devices that are less burdensome, and HMDs offering broader fields of view [29]. So this results in more reliable and detailed spatial cues, making it more likely that the user perceives the virtual environment as spatial and themselves as an integral part of it.

In the context of immersive experience design in VR, the challenge of enabling users to move through larger environments beyond the physical limits of room-scale tracking is an ongoing and iterative one. This involves implementing VR locomotion methods that allow users to navigate and explore extensive virtual spaces. Such design decisions have significant implications on performance, comfort, and presence within the VR experience, and they should be based on scientific evidence to create compelling and enjoyable user interactions.

Bowman et al. proposed a taxonomy for classifying VR locomotion methods based on their complexity [16]. The taxonomy includes key categories: 1) Travel involves controlling the user's viewpoint motion within the three-dimensional virtual environment. It encompasses different methods of moving from one location to another, such as teleportation or smooth locomotion. 2) Wayfinding is a cognitive process wherein users determine a path or route through the IVE. It relies on visual cues, the user's knowledge of the virtual space, and the availability of aids like maps or compasses within the VR experience. 3) Navigation refers to the interaction combining travel and wayfinding skills. It involves physically moving through the virtual environment and making cognitive decisions about navigating effectively within it. Generally, the focus is on navigation skills, which have higher cognitive implications for the user. When users navigate large virtual environments, they not only engage in physical movements but also need to process visual information, spatial awareness, and cognitive mapping to make informed decisions on their path and direction.

Earlier research suggests that techniques used to represent virtual walking impact the sense of presence in virtual environments [102]. However, a recent study found that the choice of locomotion method does not significantly affect the sense of presence in VR. As participants become more accustomed to the VR experience, they feel a similar level of presence regardless of the locomotion method used, or they cannot internally perceive any notable differences in presence [104]. This dissertation investigates how the locomotion methods, specifically teleportation, joystick, and real walking, would be related to the sense of presence in IVEs.

2.6 Simulator Sickness

Simulator sickness, or motion sickness in virtual environments, is a phenomenon experienced by individuals using simulators or virtual reality systems. It involves symptoms like discomfort, nausea, dizziness, and sometimes vomiting. This occurs due to a sensory conflict between the visual system's perception and the vestibular system's cues related to motion and orientation. The discrepancy between these inputs leads to motion sickness, similar to what people feel when traveling in vehicles.

Previous research has primarily investigated human factors influencing the virtual immersion experience, including gender, prior experience, and motion sickness history. Some studies indicated that females experience more simulator sickness [56], while prior experience strongly correlates with simulator sickness [60, 105]. Based on these experimental results, the same quality of the VR system can provide different user experiences depending on various human factors.

VR locomotion can induce simulator sickness due to various factors. When walking naturally, your inner ear senses motion and aligns with what your eyes see. However, in VR locomotion, you might move within a virtual environment while remaining stationary physically. This disparity between visual motion cues and absent vestibular cues can trigger a sensory conflict, causing simulator sickness [60].

Additionally, changes in motion involving acceleration and deceleration during walking are not always accurately replicated in VR, contributing to a mismatch between visual cues and physical sensations, thus promoting motion sickness. Furthermore, natural walking involves subtle sensations like the impact of steps and changes in foot pressure [98]. These sensations might be lacking or different in VR, leading to discomfort. Artificial locomotion methods, like using a joystick or controller for smooth movement, are prevalent in VR experiences. While these methods allow movement without actual walking, they can induce motion sickness due to the mismatch between physical walking and simulated training [51].

It is widely recognized that the intensity of VR sickness can be reduced through repeated exposure to the same VR content. In Freitag et al.'s research, participants who were inexperienced with VR exhibited heightened discomfort, evident in elevated SSQ scores and diminished task performance within the VR environment [40]. Hence, accounting for a user's past VR encounters is crucial when delivering VR content. Recent research more focused on the effects of VR exposure on simulator sickness like [85] that examines longitudinal trends in consumer perceptions of presence and simulator sickness in VR games. It analyzes these trends over time using data collected from the Annual Symposium on Computer-Human Interaction in Play. They studied how users' thoughts on presence and simulator sickness have evolved in the context of VR gaming.

Assessing the severity of the symptoms is crucial to diagnose and mitigate the simulator sickness symptoms. Self-reporting questionnaires are the predominant approach to quantify VR sickness, providing an intuitive means to describe one's condition. Depending on their chosen methodology, users can express their physical state through subjective or objective assessments. Earlier research primarily leaned toward subjective methods, employing a variety of questionnaire formats. More contemporary endeavors have aimed at objectively measuring discomfort levels, utilizing markers such as postural instability or physiological signals [21]. In this study, we used the SSQ questionnaire and evaluated the participants' performance to determine the level of simulator sickness during the experiment.

Chapter 3

Gait Differences in the Real World and Virtual Reality: The Effect of Prior Virtual Reality Experience

3.1 Research Design

We hypothesize that gait differences in VEs and REs will shrink for more experienced users (experience with any VR). To test this hypothesis, we designed an experiment to examine natural walking in virtual and real rooms to see VE and RE's gait differences. We recruited two groups of participants: participants with little to no experience in VR (referred to as novices) and participants with substantial prior experience in VR (referred to as experts). Participants walked controlled in real and corresponding virtual conditions to record their gait proportions. Each participant's difference in gait parameters was computed and analyzed to determine whether walking in VE, and RE varied between novice and expert users.

This section describes our experiment of measuring the gait parameters of novice and expert VR users. We ran a mixed study with two factors: walking environment (real vs. virtual worlds: within-subjects) and prior VR experience (expert vs. novice: between subjects). We designed two different conditions for running the experiments

- Virtual Space: walking with HMD for 40 trials in a virtual room.

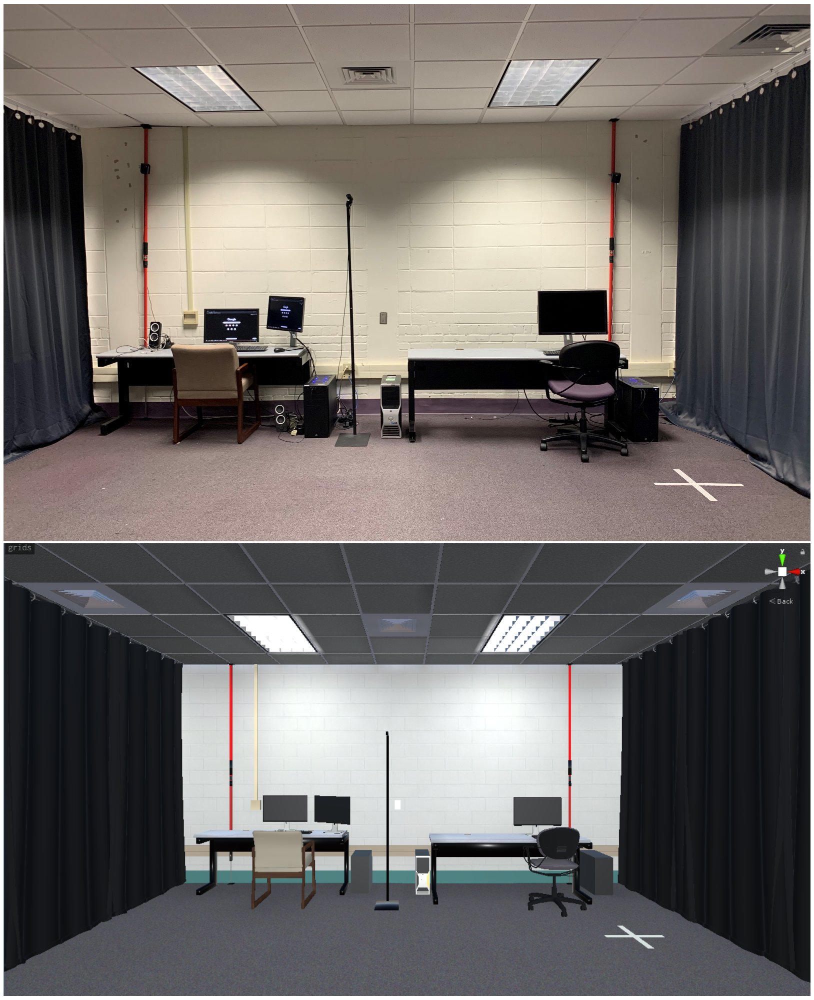

Figure 3.1: Top: Real room (Lab area), Bottom: Virtual room

- Real World: walking without HMD for 40 trials in a real room similar to the one inside the VE.

Participants performed the experiment in both conditions with counterbalanced order. Each phase has 40 trials of walking a 6 m path between two targets on the ground. Positional data from participants' bodies were collected for further analysis. We calculated the following parameters using the collected data: 1) Walking speed, 2) Step Length, and 3) Trunk angle when walking.

3.2 Environment and Equipment

Experiments took place in a fully tracked space, 10 m × 6 m in size, with a 6 m path to walk between two designated targets. This physical space has been precisely replicated in VR by using Unity (see Figure 3.1). The participants were asked to wear an HTC Vive HMD, which provides a resolution of 1080×1200 pixels per eye with an approximately 110 ° diagonal field of view and a refresh rate of 90 Hz. Four lighthouse tracking systems did positional tracking with the HTC Vive. Two HTC Vive trackers were used to track the user's feet and fastened right above the ankles. Also, subjects in the real-world phase wore one HTC Vive tracker on the hip and a hard hat with a fixed HTC-Vive tracker to track their head movements; the hard hat was chosen to make a similar condition to wearing an HMD and walking comfortable and stable. In addition to detecting and tracking their hands' position, they carried an HTC-Vive controller in their hands. Participants walked back and forth along the 6-meter path between two targets for 80 trials. These experiments have been done in VR and real-world conditions, wearing the HMD for walking in the virtual room and the hard hat to walk in the real-room condition.

Figure 3.2: A user wearing four HTC Vive trackers to track his body movements during walking

3.3 Participants

We have recruited 30 participants, 17 novices (9 men, eight women) who had less than 5 hours of experience with VR applications and 13 expert VR users (10 men, three women) with more than 20 hours of VR experience. Participants who participated in the experiment were students at Clemson University. Nineteen were men, and 11 were women, with an average age of 24 (18-38 years). All had normal or corrected-to-normal sight with contact lenses. Our participants reported no vision or equilibrium disorders. Moreover, all of them were naive to the experimental conditions they experienced and wore their everyday clothes. Four participants had never worn a VR headset before this experiment; the rest had used HTC Vive and Oculus Rift HMDs. The participants' study time, including pre-questionnaires, instructions, setting up the trackers, running the experiment, post-questionnaires, and interviewing, was about 30 minutes.

3.4 Procedure

Participants were recruited primarily from computer science and psychology departments; they received a $10 US gift card or credit for their course. Upon arrival, participants were told the experiment's procedure and signed a consent form. Then, all participants filled out a pre-questionnaire about their demographic information and backgrounds in VR. Afterward, feet and hip trackers were affixed to their ankles and back. They were asked to wear HMD or hard hats and grab controllers based on the first condition, either VR or real-world.

After calibrating the trackers by the experimenter, participants started walking back and forth between two targets marked on the ground. Participants were asked to walk at a comfortable pace between the target zones. Once they reached the target zone, participants had to turn around and walk back to their starting point. At the end of each trial, a recorded audio instruction let the participants know that one trial had been done and they could walk in the other direction. After completing the first 40 trials in an experiment condition, the experiment was switched to another condition. The experimenter provided the participants with the hard hat or HMD and asked them to stand at the start point to proceed with the experiment. So, subjects walked another 40 trials in the opposite condition for the second part of the experiment.

Immediately after finishing the experiment session, participants filled out the post-test presence questionnaire. The questionnaire consisted of 13 questions with 7-point Likert scales. Mean I-Group Presence Questionnaire (IPQ) score [94] for the feeling present in the VE was M= 4.9, indicating a relatively good sense of presence in VR. After completing the questionnaires, the experimenter interviewed participants asking questions about their perception and understanding during the experiment. In the end, participants were invited to give feedback regarding the experiment.

3.5 Results: Comparing expert and novice users' gait parameters

We assumed the following hypotheses:

- H1: Participants' gait parameters in VR and the real world differ.

Table 3.1: Effective variables on Walking Time

Walking Time	Coefficient/**Estimate**	**95% CI**	**T**	**p-value**	**Std**	**Std. Coef. 95% CI**
Modality	0.86	$[+0.55, +1.16]$	5.50	$< .001$	0.38	$[+0.17, +0.59]$
Expertise	0.66	$[-0.16, +1.48]$	1.58	0.115	0.35	$[-0.24, +0.94]$
Trial	3.86e-03	$[0.00, +0.01]$	1.98	0.048	0.03	$[0.00, +0.06]$
Modality * Trial	-0.02	$[-0.02, -0.01]$	-7.29	$< .001$	-0.14	$[-0.17, -0.10]$
Expertise * Trial	-8.74e-03	$[-0.01, 0.00]$	-3.88	$< .001$	-0.07	$[-0.11, -0.04]$

- H2: Participants with prior VR experience (experience with any VR) walk differently than novice VR users.

To analyze prior experience's effect on gait parameters, we ran statistics models comparing Expert and Novice users' gait parameters. In the first round of analysis, walking time, average speed, step count, step length, and trunk angle values for both groups of participants were assessed. The following section reports the evaluation results and describes how they would provide answers to our research questions.

We conducted linear mixed models to study human walking in the Immersive Virtual Environment. We evaluated the effects of experimental conditions (VR vs. Real World) and previous VR experience (Expert vs. Novice). We analyzed with a random intercept to account for repeated measurement data. We ran an exploratory model with modality, previous VR experience, trial ID as Independent Variables(IVs), and gait parameters as Dependent Variables (DV). We used the ”buildmer” function from the CRAN package in R Studio. Buildmer performs backward step-wise elimination based on multiple criteria, such as a change in log-likelihood, AIC, and BIC, and converges a maximal model [115].

3.5.1 Walking Time(s)

After examining the full model containing Expertise (Experienced Novice), Modality (Real Virtual), and Trial ID, the best-fit model (using the BIC criteria) was determined. It included Expertise, Modality, and Trial as fixed effects, along with 2-way interaction effects; Expertise*Trial and Modality*Trial. The linear mixed model parameters for walking time are reported in Table 3.1.

The model's total explanatory power is substantial (conditional R^2 = 0.82), and the part related to the fixed effects alone (marginal R^2) is 0.07. The model's intercept, corresponding to Modality, Expertise, and Trial, is at 6.67 (95% CI [6.09, 7.26], t(2208) = 22.43, $p < .001$). Based on the results, the effect of Modality

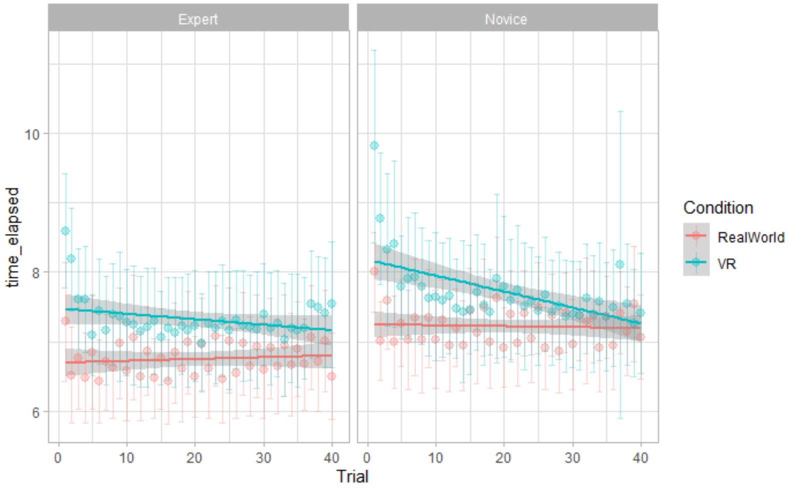

Figure 3.3: Time to complete the 40 trials for novice and expert users labeled by their prior experience level

is statistically significant and positive (beta = 0.86, 95% CI [0.55, 1.16], t(2208) = 5.50, $p < .001$; Std. beta = 0.38, 95% CI [0.17, 0.59]). However, the effect of Expertise is statistically non-significant and positive (beta = 0.66, 95% CI [-0.16, 1.48], t(2208) = 1.58, p = 0.115; Std. beta = 0.35, 95% CI [-0.24, 0.94]). In addition, the effect of the Trial is statistically significant and positive (beta = 3.86e-03, 95% CI [3.98e-05, 7.67e-03], t(2208) = 1.98, $p < .05$; Std. beta = 0.03, 95% CI [3.32e-04, 0.06]). Considering two-way interactions, the interaction effect between Trial on Modality is statistically significant and negative (beta = -0.02, 95% CI [-0.02, -0.01], t(2208) = -7.29, $p < .001$; Std. beta = -0.14, 95% CI [-0.17, -0.10]). Also, the interaction effect between Trial on Expertise is statistically significant and negative (beta = -8.74e-03, 95% CI [-0.01, -4.33e-03], t(2208) = -3.88, $p < .001$; Std. beta = -0.07, 95% CI [-0.11, -0.04]).

While the average time for users to walk one trial in the VR was 7.643 seconds, the average time to walk the same distance without VR headsets was 7.067 seconds. As shown in Figure3.3, walking time for both groups of users was significantly higher in VR. The graph also shows that walking time is reduced over time by completing more trails. It may bring us an important learning pattern with technology usage; more walking time in VR makes users faster in taking steps.

Our initial assumption was that walking time in the real world would be the same for both novices and experts. However, evaluating the results showed that experts spent less time in both VR and real-world conditions. Consequently, this unexpected result made us analyze more variables to find a meaningful pattern to describe this outcome. We noticed that the order of the experiment's conditions affected the walking time. So, we added Modality Order (VR first vs. RW first) as another independent variable to the analysis. We

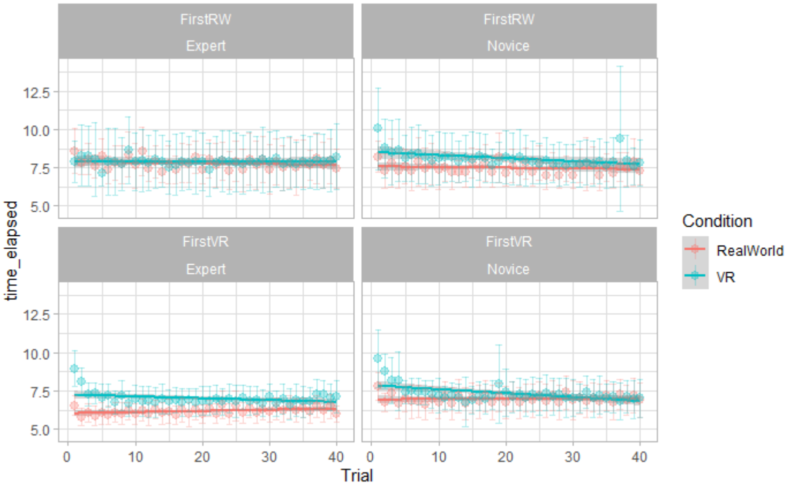

Figure 3.4: Walking time of the 40 trials by experienced and novice users labeled by first VR and first RW as the first condition of experiment

found a two-way interaction effect between Modality Order and Trial ID, suggesting that walking time for both groups of subjects, either first walked in VR or real-world, has decreased from the first trials to the last ones ($p < .001$). Also, the results showed a significant three-way interaction effect between Modality Order, Modality, and Trial ID.

The relationship between Modality, Trial ID, Expertise, and Modality Order on the Walking Time is shown in Figure 3.4. It suggests that subjects in a VR environment walked more quickly than in the real world. In addition, those who first walked in the VR space walked quicker in the later trials and spent less time than those who first walked in the real world ($p < .001$). Participants who started the experiment with the VR phase sooner adapted to handling the VR hardware while walking.

As a part of the experiment procedure, subjects were asked to wear trackers on their feet and hip. Also, they wore a VR headset (in VR) and a hard hat (in real space). Carrying this equipment might be a factor that made novices slower than experts. When they started walking in the real world, they only wore trackers and a hard hat. When they walked into VR, they had both VR hardware to carry and stepped into a relatively new environment. One possible explanation would be that novices who started with VR used new devices on their bodies and simultaneously entered a new world. However, novices who started with the real world carried less weight and figured out how to walk with the devices in a less complex set in a real lab area. Therefore, there could have been a carry-over effect for novices, such that their experience of walking at higher speed in the real world might have carried over to the virtual world.

Table 3.2: Effective variables on Average Speed per Trial

Average Speed	Coefficient/**Estimate**	**95% CI**	**T**	**p-value**	**Std**	**Std. Coef. 95% CI**
Modality	-0.09	$[-0.13, -0.06]$	-5.27	$< .001$	-0.36	$[-0.57, -0.15]$
Trial	6.58e-04	$[0.00, 0.00]$	3.68	$< .001$	0.05	$[+0.02, +0.07]$
Modality * Trial	1.84e-03	$[0.00, 0.00]$	7.28	$< .001$	0.13	$[+0.10, +0.17]$

3.5.2 Average Speed m/s

The average speed has been calculated using equation 3.2 in which the speed is generated using the ΔD and Δt (equation 3.1).

$$\Delta V_i = \frac{\Delta D_i}{\Delta t_i}\text{ , where } \begin{cases}\Delta t_i = t_{i+1} - t_i\end{cases} \tag{3.1}$$

$$V = \frac{1}{N}\sum_{i=1}^{N-1} \Delta V_i \tag{3.2}$$

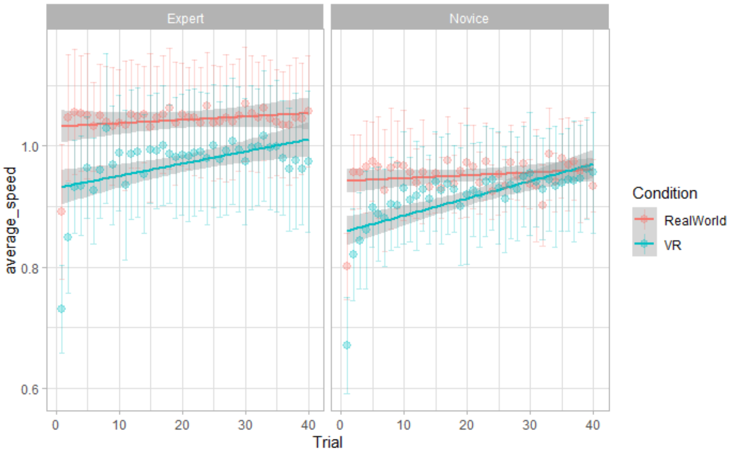

Figure 3.5: Average Speed influenced by Modality and Expertise

Our results showed that participants walked quicker in the real world p< .001. While the mean speed for walking in the VR was 0.954, participants walked in the real space with a speed of 1.009 m/s. Furthermore,

Table 3.3: Effective variables on Step Count per Trial

Step Count	Coefficient/**Estimate**	**95% CI**	**T**	**p-value**	**Std**	**Std. Coef. 95% CI**
Expertise	0.62	$[-0.12, +1.37]$	1.65	0.099	0.32	$[-0.18, +0.82]$
Modality	0.40	$[+0.11, +0.70]$	2.69	0.007	0.16	$[-0.01, +0.33]$
Trial	7.94e-03	$[0.00, +0.01]$	2.47	0.014	0.06	$[+0.01, +0.11]$
Modality * Trial	-8.38e-03	$[-0.02, 0.00]$	-2.22	0.026	-0.07	$[-0.12, -0.01]$
Expertise * Trial	-7.56e-03	$[-0.01, 0.00]$	-2.01	0.045	-0.06	$[-0.12, 0.00]$

on average, novices had a lower speed than experts $p < .001$. Adding Trial ID numbers to the analysis revealed a significant effect of Trial and Modality on average speed (See fig.3.10).

Table 3.2 shows details of our full model containing Expertise, Modality, and Trial. The best-fit model (using the BIC criteria) is determined to include Modality and Trial as fixed effects and 2-way interaction effects between Modality and Trial.

We fitted a linear mixed model to predict Average Speed with Modality and Trial. The model's total explanatory power is substantial (conditional $R^2 = 0.82$), and the part related to the fixed effects alone (marginal R^2) is 0.05. The model's intercept, corresponding to Condition = Real World and Trial = 0, is at 0.99 (95% CI [0.93, 1.04], t(2196) = 36.60, $p < .001$). In this model, the effect of Modality is statistically significant and negative (beta = -0.09, 95% CI [-0.13, -0.06], t(2196) = -5.27, $p < .001$; Std. beta = -0.36, 95% CI [-0.57, -0.15]). In addition, the effect of the Trial is statistically significant and positive (beta = 6.58e-04, 95% CI [3.08e-04, 1.01e-03], t(2196) = 3.68, $p < .001$; Std. beta = 0.05, 95% CI [0.02, 0.07]). The interaction effect of Trial on Modality is statistically significant and positive (beta = 1.84e-03, 95% CI [1.35e-03, 2.34e-03], t(2196) = 7.28, $p < .001$; Std. beta = 0.13, 95% CI [0.10, 0.17]).

Examining the results showed an increase in velocity by walking more trials. It may conclude that participants walked slowly in the beginning trials because they were not thoroughly familiar with the system. As they made some trials, they learned the system interaction and walked more quickly. Thus, the walking behavior of participants shows evidence of calibration; as participants gained comfort with the condition they were experiencing, they tended to walk at a higher velocity.

3.5.3 Step Count

Wendt et al. suggested a gait-based state model categorized into four states (no gait, single foot initial swing, single foot terminal swing, and post-single foot double support), and each state is altered by four gait

Table 3.4: Effective variables on Step length per Trial

Step Length	Coefficient/**Estimate**	**95% CI**	**T**	**p-value**	**Std**	**Std. Coef. 95% CI**
Expertise	-0.21	$[-0.43, +0.01]$	-1.84	0.066	0.23	$[-0.63, +0.18]$
Modality	-0.21	[-0.32, -0.11]	-3.86	$< .001$	-0.15	$[-0.31, 0.02]$
Trial	-5.73e-03	$[-0.01, 0.00]$	-3.91	$< .001$	-0.13	$[-0.19, -0.06]$
Expertise * Trial	4.36e-03	$[0.00, +0.01]$	2.54	0.011	0.10	[+0.02, +0.17]
Modality * Trial	6.72e-03	$[0.00, +0.01]$	3.93	$< .001$	0.15	[+0.07, +0.22]

events (foot-off, max foot height, foot-strike, gait stop) [118]. So, the gait experience is concluded as follows: Foot Off happens when a single foot is leaving the ground; Max Foot Height has been identified if the moving ankle's vertical velocity decreases below a threshold. Foot Strike happens when the moving foot contacts the ground. Gait Stop happens when the moving single foot touches the floor in the foot's initial swing state. If a gait stop is detected, the system returns to the no gait state.

We have used the method that [123] suggests for step detection. In this paper, to keep the results consistent, we only used the position of the left foot. Both step count and step length are calculated for the left foot.

After examining the full model containing Expertise, Modality, and Trial, the best-fit model (using the BIC criteria) was determined to include Expertise (p $<$ .1), Modality (p $<$ .01), and Trial (p $<$ .05) as fixed effects, along with two-way interaction effects between Expertise and Trial (p $<$ .05) plus Modality and Trial (p $<$ .05) The linear mixed model parameters for step count are reported in Table 3.3. The estimate column reports the average change of the left foot step number influenced by the experiment variables (the slope in a linear model).

Based on the results shown in figure3.6 number of steps in the VR environment is significantly higher than in the Real World (p = 0.007). Also, step numbers gradually decrease for novice users while expert users stay with a fixed step number until the end of trials (p = 0.044). Results match our assumption that VR users walk more confidently in the real world than in the VR space. Considering users walking patterns reveals that novice users get more confident by walking in VR; their step numbers are slightly lower in the last trials.

Standardized parameters were obtained by fitting the model on a standardized dataset version. 95% Confidence Intervals (CIs) and p-values were computed using the Wald approximation. We fitted a linear mixed model to predict Step Count with Expertise, Modality, and Trial. The model's total explanatory power is substantial (conditional R2 = 0.59), and the part related to the fixed effects alone (marginal R2) is 0.03. The

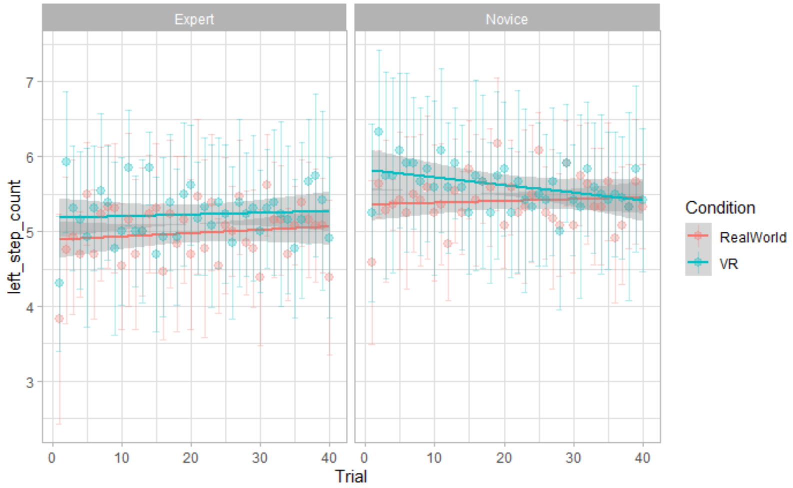

Figure 3.6: Left Step Count influenced by Modality during the experiment time

model's intercept is at 4.79 (95% CI [4.26, 5.31]). Within this model, the effect of Expertise is statistically non-significant and positive (beta = 0.62, 95% CI [-0.12, 1.37], t(1969) = 1.65, p = 0.099, Std. beta = 0.32). However, the effect of Modality is statistically significant and positive (beta = 0.40, 95% CI [0.11, 0.70], t(1969) = 2.69, $p < .01$, Std. beta = 0.16). The effect of the Trial is also statistically significant and positive (beta = 7.94e-03, 95% CI [1.63e-03, 0.01], t(1969) = 2.47, $p < .05$, Std. beta = 0.06). Also, the interaction effect between Trial and Modality is statistically significant and negative (beta = -8.38e-03, 95% CI [-0.02, -9.94e-04], t(1969) = -2.22, $p < .05$, Std. beta = -0.07). In addition, the interaction effect between Trial and Expertise [Novice] is statistically significant and negative (beta = -7.56e-03, 95% CI [-0.01, -1.71e-04], t(1969) = -2.01, $p < .05$, Std. beta = -0.06).

3.5.4 Step Length

The distance between two consecutive placements of the same foot on the ground is labeled step length. Points of contact are determined from the translation of the foot tracker. Equation 3.4 gives us the desired distance.

$$\Delta D_i = \sqrt{x_i^2 + y_i^2 + z_i^2}\ , \text{ where } \begin{cases} \Delta x_i = x_{i+1} - x_i \\ \Delta y_i = y_{i+1} - y_i \\ \Delta z_i = z_{i+1} - z_i \end{cases} \tag{3.3}$$

$$D = \sum_{i=1}^{N-1} \Delta D_i \tag{3.4}$$

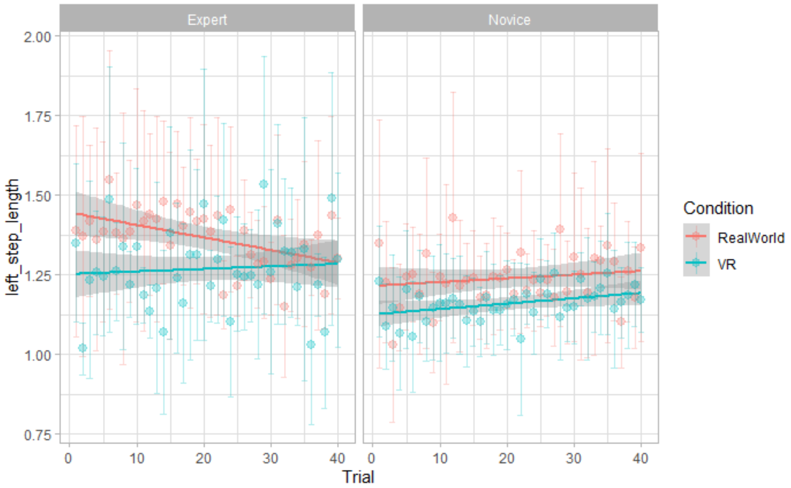

Figure 3.7: Step Length changes over time of experiment by effects of Expertise and Modality

We fitted a linear mixed model to predict Step Length with Expertise, Modality, and Trial. The model's total explanatory power is substantial (conditional R2 = 0.31), and the part related to the fixed effects alone (marginal R2) is 0.03. The model's intercept, corresponding to Expertise = Expert, Condition = Real World and Trial = 0, is at 1.52 (95% CI [1.36, 1.68], t(1969) = 18.50, $p < .001$). Within this model, the effect of Expertise is statistically non-significant and negative (beta = -0.21, 95% CI [-0.43, 0.01], t(1969) = -1.84, p = 0.066; Std. beta = -0.23, 95% CI [-0.63, 0.18]). The effect of Modality is statistically significant and negative (beta = -0.21, 95% CI [-0.32, -0.11], t(1969) = -3.86, $p < .001$; Std. beta = -0.15, 95% CI [-0.31, 0.02]). The effect of Trial is statistically significant and negative (beta = -5.73e-03, 95% CI [-8.59e-03, -2.86e-03], t(1969) = -3.91, $p < .001$; Std. beta = -0.13, 95% CI [-0.19, -0.06]). The interaction effect between the Trial and Expertise [Novice] is statistically significant and positive (beta = 4.36e-03, 95% CI [1.00e-03, 7.71e-03], t(1969) = 2.54, $p < .05$; Std. beta = 0.10, 95% CI [0.02, 0.17]). The interaction effect between Trial and Modality is statistically significant and positive (beta = 6.72e-03, 95% CI [3.36e-03, 0.01], t(1969) = 3.93, $p <$ .001; Std. beta = 0.15, 95% CI [0.07, 0.22]).

3.5.5 Trunk Angle

The trunk angle is the angle between the trunk segment and a vertical axis in the longitudinal plane. This angle is represented in figure 3.8 as θ_2; it would be positive if one leans back against the vertical line [122].

Table 3.5: Effective variables on Trunk Angle

Trunk Angle	Coefficient/**Estimate**	**95% CI**	**T**	**p-value**	**Std**	**Std. Coef. 95% CI**
Expertise	-0.09	$[-0.26, +0.07]$	-1.11	0.269	-0.14	$[-0.40, +0.12]$
Modality	+0.36	$[-0.06, +0.79]$	1.68	0.093	0.52	$[-0.16, +1.21]$
Trial	-2.18e-03	$[0.00, 0.00]$	-2.58	0.010	-0.04	$[-0.07, -0.01]$
Expertise * Modality	-0.45	$[-1.06, +0.16]$	-1.45	0.146	-0.54	$[-1.52, +0.45]$
Expertise * Trial	4.60e-04	$[0.00, 0.00]$	0.38	0.707	8.63e-03	$[-0.04, +0.05]$
Modality * Trial	-2.03e-03	$[0.00, 0.00]$	-1.68	0.093	-0.04	$[-0.08, +0.01]$
Expertise * Modality * Trial	6.02e-03	$[0.00, +0.01]$	3.46	$< .001$	0.11	$[0.05, +0.18]$

So, if a user stands in a position like figure 3.8, his/her trunk angle would be negative. As results show, experts' trunk angle in VR condition represents that they were more upright walking with HMD than novices. Novice VR users need to lean forward to take steps, while experts unconsciously adopt the field of view and manage walking without looking down. However, the graph shows that experts walked differently in VR and real-world sessions. We may explain it by users' curiosity to look around and explore the virtual space. In comparison, novices were mainly focused on walking and reaching the targets on the ground.

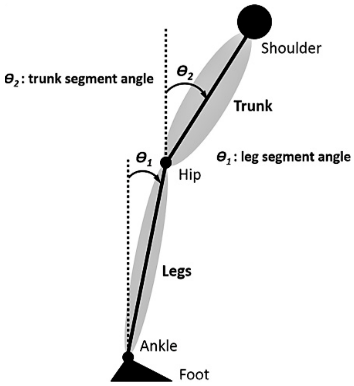

Figure 3.8: Trunk angle [49]

We fitted a linear mixed model to predict Trunk Angle with Expertise, Modality, and Trial. The model's total explanatory power is substantial (conditional R2 = 0.88), and the part related to the fixed effects alone (marginal R2) is 0.06. The model's intercept is at -0.12 (95% CI [-0.24, -3.76e-03]). Within this model: the effect of Expertise is statistically non-significant and negative (beta = -0.09, 95% CI [-0.26, 0.07], t(2116) = -1.11, p = 0.269, Std. beta = -0.14). The effect of Modality is statistically non-significant and positive (beta = 0.36, 95% CI [-0.06, 0.79], t(2116) = 1.68, p = 0.093, Std. beta = 0.52). The effect of Trial is statistically

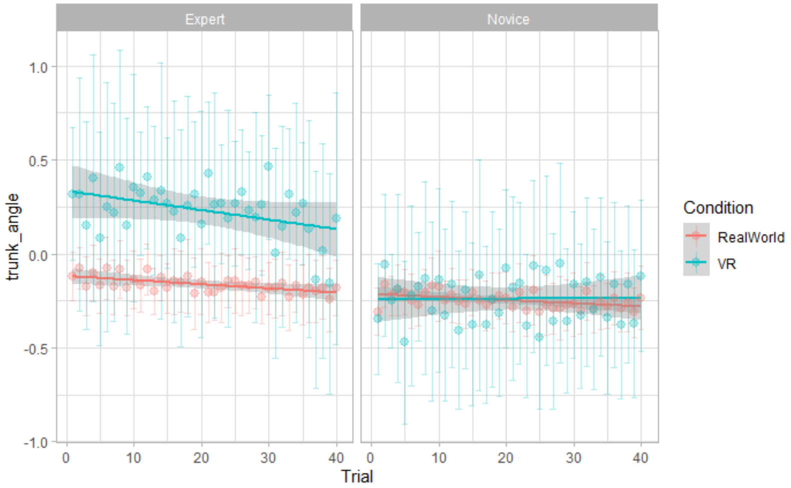

Figure 3.9: Relationship between Modality and Expertise effects on Trunk Angle

significant and negative (beta = -2.18e-03, 95% CI [-3.84e-03, -5.23e-04], t(2116) = -2.58, p < .01, Std. beta = -0.04). The interaction effect between Modality and Expertise is statistically non-significant and negative (beta = -0.45, 95% CI [-1.06, 0.16], t(2116) = -1.45, p = 0.146, Std. beta = -0.54). The interaction effect between Trial and Expertise is statistically non-significant and positive (beta = 4.60e-04, 95% CI [-1.94e-03, 2.86e-03], t(2116) = 0.38, p = 0.707, Std. beta = 8.63e-03). The interaction effect between Trial and Modality is statistically non-significant and negative (beta = -2.03e-03, 95% CI [-4.40e-03, 3.36e-04], t(2116) = -1.68, p = 0.093, Std. beta = -0.04). The 3-way interaction effect between Trial, Expertise, and Modality is statistically significant and positive (beta = 6.02e-03, 95% CI [2.61e-03, 9.44e-03], t(2116) = 3.46, p < .001, Std. beta = 0.11).

Linear-mixed models (LMMs) were used to analyze the experiment results and verify the hypotheses. So, models were created in R [86] first using the 'buildmer' [115] and 'lme4' [6] R packages. Buildmer automatically tests different possible models based on a set of independent variables and uses the model's likelihood-ratio test and the minimum Bayesian information criterion to select the model that best matches the observed data [95]. Once the final model was specified, it fitted to the data using the lmer command provided by lme4. The lmerTest package [6] was used to estimate p-values using the Satterthwaite degrees of freedom method [93] for the models generated by lmer. The figures were generated using ggplot2 [119]. Equivalence tests were performed using the TOSTER package in R.

3.6 Results: Gait parameters difference based on expertise and trial numbers

We consider three independent variables in this study: 1) walking speed, 2) step length, and 3) trunk angle. These gait parameters got evaluated based on the subjects' expertise and the trial numbers. Our primary interest was how the difference in gait between the real world and VR gets moderated by prior experience using VR. We first computed the delta between participants' gait in the real world and VR for each metric and then used this value in our analysis. According to this convention, a positive delta value indicates that the metric was greater in the real world (e.g., a positive delta speed indicates that participants walked more quickly in the real world).

3.6.1 Average Speed m/s

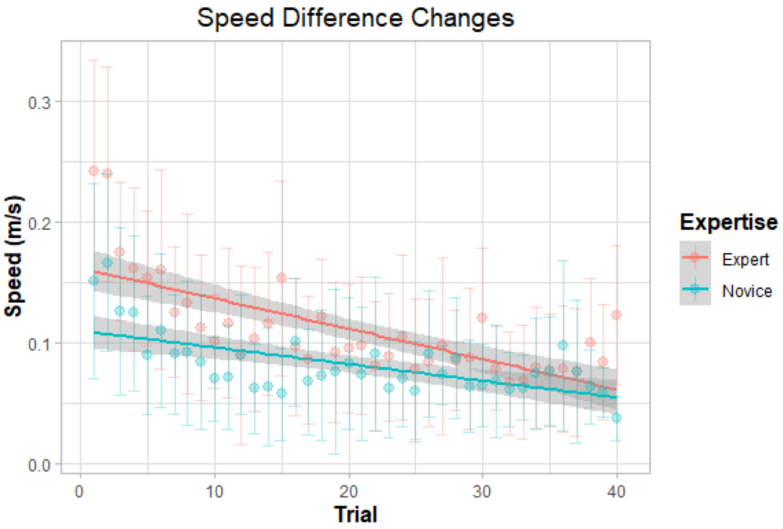

Figure 3.10: Difference between experts and novices average speed in VR and Real-World. The average speed for walking in the IVE was 0.954 m/s, and for walking in the real room was 1.009 m/s

Standardized parameters were obtained by fitting the model on a standardized version of the data set. 95% Confidence Intervals (CIs) and p-values were computed using the Wald approximation. We fitted a linear mixed model to predict Delta Velocity with Trial Number and Expertise. The model included Participant Identification Number (PID) as a random effect. The model's total explanatory power is substantial (conditional $R^2 = 0.56$), and the part related to the fixed effects alone (marginal R^2) is 0.07. The model's intercept is at 0.16 (95% CI [0.12, 0.20]). Within this model:

The effect of Trial is statistically significant and negative (β = -2.52e-03, 95% CI [-3.00e-03, -2.04e-03], t(1094) = -10.28, $p < 0.001$, Std. β = -0.30). Moreover, effect of Expertise(Novice) is trending towards significance and negative (β = -0.05, 95% CI [-0.11, 1.90e-03], t(1094) = -1.89, p = 0.059, Std. β = -0.29). Also, the interaction effect of Expertise on Trial is statistically significant and positive (β = 1.18e-03, 95% CI [5.04e-04, 1.86e-03], t(1094) = 3.42, $p < 0.001$, Std. β = 0.14). This interaction effect significantly affected the subject's walking, as observed in the experiment location and graphs. We performed an equivalence test on the effect of expertise and found that the changes in speed between experts and novices were equivalent to each other within a range of ± 0.04 meters/second.

Novices and experts walked at different speeds in VR and the real room setups; both were faster in the Real World than in the VE. Figure 3.10 shows the graph of speed changes during the experiment. The red line displays the experts' velocity shifts over time, as depicted in the graph. The graph shows that experts' performance in the last trials was more similar than in the first trials. Likewise, the same pattern is observed for novices' walking velocity; the blue line depicts how their performance dissimilarity in the start trials diminishes over time by walking more trials. For both groups, the more trials were completed, the more distinctions turned into similarities.

3.6.2 Step Length

Step length was defined as the distance between two consecutive placements of the same foot on the ground. Points of contact were located based on tracking data from the HTC Vive tracker on participants' feet. We have used the suggested method in [123] for step detection. The average step length was then computed by taking the average length of each step taken in one trial.

Standardized parameters were obtained by fitting the model on a standardized dataset version. 95% CIs and p-values were computed using the Wald approximation. We fitted a linear mixed model to predict Delta Step Length with Trial. The model included PID as a random effect. The model's total explanatory power is substantial (conditional R^2 = 0.36), and the part related to the fixed effects alone (marginal R^2) is 3.03e-03. The model's intercept is at 0.36 (95% CI [0.24, 0.48]). Within this model, the effect of the Trial is statistically significant and negative (β = -2.26e-03, 95% CI [-4.30e-03, -2.15e-04], t(992) = -2.17, $p < 0.05$, Std. β = -0.06). We performed an equivalence test on the effect of expertise and found that the changes in step length between experts and novices were equivalent to each other within a range of ± 0.13 meters. The above statistics have indicated the trial as a significant variable affecting the step length. Likewise, the graph illustrates the average step length distinctions over trials (see Figure 3.11).

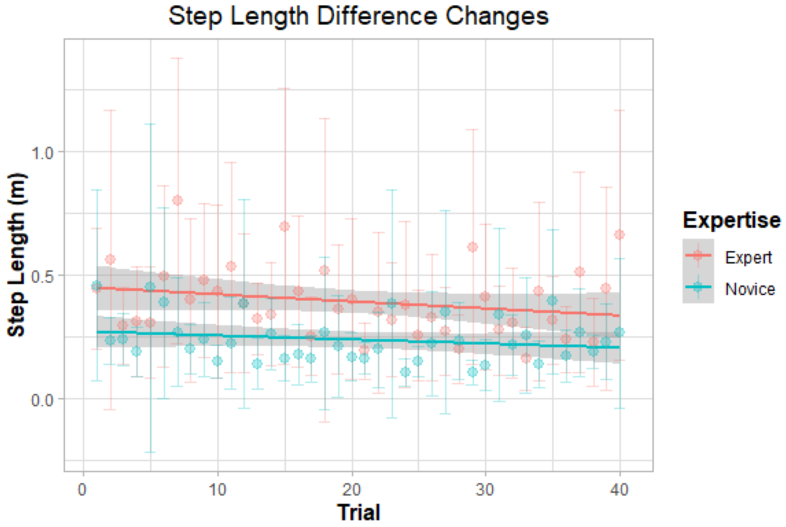

Figure 3.11: Step Length changes over time of experiment; when an expert's step held an average length of 1.4 m, the average step length for a novice was 1.2 m

3.6.3 Trunk Angle

A trunk angle is between the trunk segment and a vertical axis in the longitudinal plane. This angle is represented in Figure 3.8 as θ_2; it would be positive if one leans back against the vertical line [122]. So, if a user stands in a position like Figure 3.8, his/her trunk angle would be negative.

We fitted a linear mixed model (estimated using REML and nloptwrap optimizer) to predict Delta Trunk-Angle (DeltaTA) by changes of Expertise and Trial, including PID as a random effect. The model's total explanatory power is substantial (conditional $R^2 = 0.83$), and the part related to the fixed effects alone (marginal R^2) is 0.07. The model's intercept, corresponding to Expertise = Expert and Trial = 0, is at 0.75 (95% CI [0.46, 1.04], t(710) = 5.04, $p < 0.001$). Within this model, the effect of Expertise is statistically non-significant; however, the effect of Trial is statistically significant and negative (β = -2.59e-03, 95% CI [-4.46e-03, -7.29e-04], t(701) = -2.73, $p < 0.01$; Std. β = -0.05, 95% CI [-0.09, -0.01]). Moreover, there is an interaction effect of Trial on Expertise that is statistically significant and positive (β = 4.17e-03, 95% CI [2.16e-04, 8.13e-03], t(701) = 2.07, $p < 0.05$; Std. β = 0.08, 95% CI [4.17e-03, 0.16]). We performed an equivalence test on the effect of expertise and found that the changes in trunk angle between experts and novices were equivalent to each other within a range of ±0.3 degrees.

Experienced subjects walked more upright in the IVE than in the real environment, and novices walked in VR while leaning forward. As statistics revealed, the trial was a significant variable, so the subjects' poses changed over trials. While a main effect of expertise was not observed, an interaction effect between

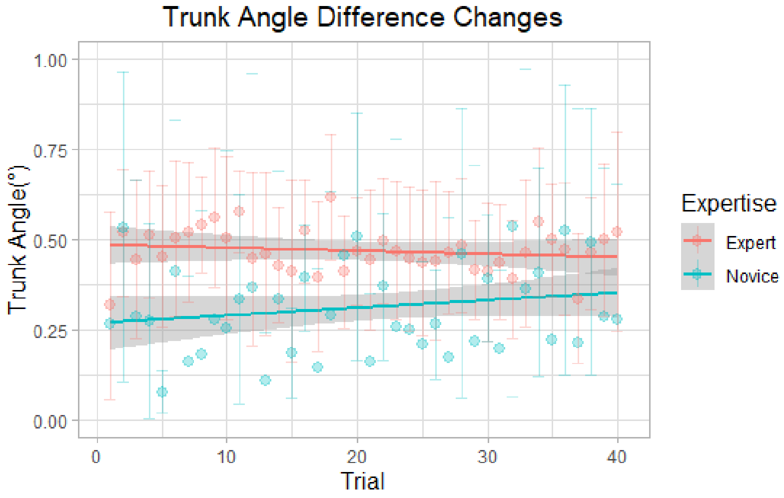

Figure 3.12: Difference of participants' Trunk Angle in the IVE and Real World over the 40 trials

expertise and the trial number was present, such that the difference in trunk angle increased over time for novices but decreased over time with experts (see Figure 3.12).

3.7 Discussion

Walking is one of the most fundamental tasks for moving in VR applications such as training, health care, and education. The principal purpose of this study was to examine if and to what extent novice and experienced VR users walk differently in immersive virtual environments. We collected valuable results to find gait differences between novice and expert subjects.

Results showed that walking time for both groups of participants was significantly higher in VR, and it was reduced by completing more trails. However, experienced VR users needed less time for both phases; they traveled the path faster than novices in VR and Real-World conditions. One possible explanation for the difference between novice and experienced VR users is that expert users may have enhanced perception-action coordination from prior VR experience. This prior VR experience may have enabled them to perceive the optic flow in VR simulations better and execute motor effort to maintain a comfortable travel speed; support for this explanation can be found in driving and bicycling simulator research [25, 26].

Furthermore, novices had a lower speed than experts $p < 0.001$. As a part of the experiment procedure, subjects were asked to wear trackers on their feet and hip. Also, they wore a VR headset (in VR) and a hard hat (in the real session). Carrying all the equipment might be a factor that made novices slower than experts.

When they started walking in the real world, they only wore trackers and a hard hat. When they walked into VR, they had both VR hardware to carry and stepped into a relatively new environment.

In addition, the difference between the average length of steps in VR and the real world is higher for expert users. So, the results matched our assumption that VR users' prior experience leads to differences in their behavior. They took relatively larger steps in a VR setting than in a real room.

Furthermore, novice participants inclined forward to take steps, while experts were more upright when walking on the path. We may explain it by expert users' curiosity to look around and explore the virtual space. In comparison, novices were mainly focused on walking and reaching the targets on the ground.

In future research, we would like to explore the question, what if experts had more experience using alternative interfaces but not walking? It would lead to some potential follow-up studies for further research. Future work will also include the analysis of gait behaviors of experienced and novice VR users in other tasks, such as collision avoidance and gap crossing.

3.8 Conclusion

This chapter aimed to compare gait parameters in VR and the real world. The parameters include speed, step length, and trunk angle. So, the gait characteristics for two conditions and two classes of users were analyzed to assess the effect of the prior VR experience. We compared the differences between velocity, step length, and body angle for each participant in VR versus the Real world. The more people experience VR, their walking parameters differ in VR and the real room. Our findings illustrate that the VR experience may make users self-calibrate and distinguish actions in the two conditions.

Chapter 4

Changes in Navigation Over Time: A Comparison of Teleportation and Joystick-based Locomotion

4.1 Research Design

In this chapter, we report the results of a longitudinal experiment where participants completed a navigation activity four times during a four-week period. Before beginning the experiment, participants were randomly assigned to one of two between-subject conditions: 1) using teleportation for locomotion or 2) using joystick-based locomotion. Participants were assigned ten navigation trials each time they performed the activity, during which the time required to complete the task and their accuracy with a spatial updating task was measured. Participants also completed the Simulator Sickness Questionnaire [57] and the iGroup presence questionnaire [94].

We hypothesize that the change in participants' locomotive performance correlates with the locomotion technique they use in VR. Also, we expected to see an effect of time/experience on participants' locomotion and navigation performance in IVE. Our research questions were as follows:

RQ1: Will participants' locomotive behaviors change between sessions as they become more familiar with VR?

RQ2: Will a different pattern of change be observed between locomotive methods?

RQ3: Will the effects of the locomotion method on simulator sickness change with time?

RQ4: Will the effects of the locomotion method on presence change with time?

4.2 Environment and Equipment

Twenty different floorplans were automatically generated using the Dungeon Architect plugin [111] for Unity. All floorplans were designed with the following constraints: 1) the main path from start to finish was 8 rooms long, 2) four side paths containing three rooms ending in a dead-end, 3) a key-card was placed at the final room of one of these side paths, 4) a locked door that could be opened with the keycard was placed on the main path after the four side paths. All rooms were directly connected to other rooms; no corridors were in the floorplans. These rules ensured that the different floorplans contained the same number of rooms, the same connectivity, and the shortest path of the same length (crossing through 10 unique doorways, 3 of which were traversed twice). Example floorplans can be seen in Figure 1, and an example of a typical room can be seen in Figure 5.2.

Locomotion was implemented using VRTK 4 [1] and the VRTK Prefabs v1.1.8 [36]. Joystick locomotion was calibrated to move participants at a constant speed of 2.25 meters per second, equivalent to a fast walk. Pushing forward on the joystick would translate participants in the direction they were facing; participants could move side-to-side or backward by pushing the joystick in the appropriate direction. A dead zone of 10% was used to prevent very slight adjustments of the joystick from moving participants. Teleportation was implemented where participants pressed down on the trigger to activate a parabolic raycast that could be used to select where they wanted to move to. Once they had indicated where they wanted to move using the raycast, participants released the trigger to teleport to that location. Teleportation occurred instantaneously without any fading of the scene view. The maximum distance participants could teleport at once was 10 meters.

4.3 Participants

Twenty people participated in this study (five females and one non-binary). Ages ranged from 18 to 33 years old, with a median age of 20. All participants had normal or corrected-to-normal vision. Participants were recruited via an email sent to undergraduate and graduate students at Clemson University.

---

[1] https://www.vrtk.io/

The participants were recruited based on the below prerequisites: 1) having less than 1 hour of prior experience using VR, 2) volunteering to commit to using the HMD regularly for four weeks, 3) being ready to complete detailed activities as part of the experiment every week, 4) approving not to let anyone else use the device, 5) confirmation of having an open floor space at home that could be used for the Quest, and 6) participating in two interviews during the study. Participants received a $50 Visa gift card when enrolling in the study and a $75 Amazon gift card after finishing the study.

4.4 Procedure

Each participant was loaned an Oculus Quest for the experiment duration (four weeks). Upon picking up the HMD, participants were provided with straightforward instructions about 1) operating the headset, 2) using the Sidequest application [2] to load the custom activities onto the Quest, 3) and accessing data saved to the headset about their activities. Each week, participants were requested to upload log files about their activity to a specific Google Drive folder created for each participant. This allowed us to keep track of their progress and remind participants who fell behind.

Participants were asked to complete three activities each week and any personal use they were interested in (e.g., games, entertainment, etc.). Participants were instructed to complete no more than one of our activities on any given day so as to avoid any immediate effects of one activity on another activity. Participants accessed our custom activities via a single application. Participants completed three custom activities in counterbalance order: 1) an activity assessing sensitivity to rotational gains, 2) an activity assessing sensitivity to proprioceptive offsets, and 3) a navigation activity. Activities 1 and 2 were completed while stationary; no locomotion or navigation was required from participants. A brief description of each of these activities is included below. This paper only reports the results of the Navigation activity, which is focused on locomotion and navigation in VR over time.

Rotational Gain activity: In this activity, participants were asked to stand in a garage environment and look at targets to the right and left in multiple trials. One of these rotations had a gain applied in each trial. Participants were then asked to identify which rotation had a gain applied to it. While rotational gains can sometimes lead to cybersickness, the average scores reported by participants were low [91].

Proprioceptive Offsets activity: In this activity, participants were asked to sit down in front of a virtual table and stack blocks at a target location. The Oculus Quest's hand tracking was enabled for this

---

[2] https://sidequestvr.com/

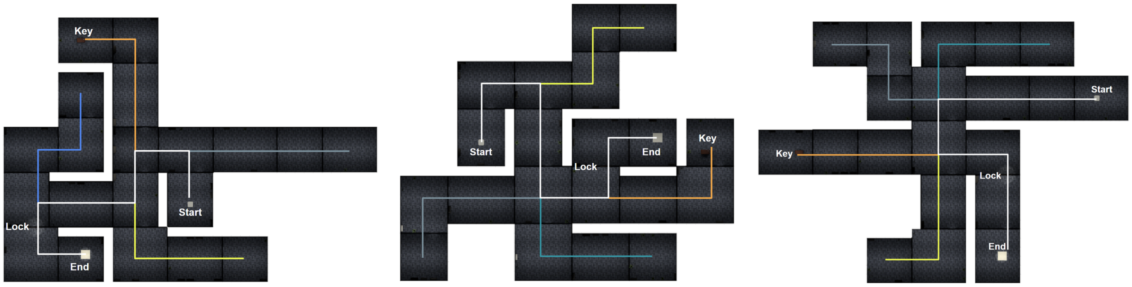

Figure 4.1: Three examples of generated levels. In these images, the main path from start to end is shown in white, and the side path to the key is colored orange. The other colored paths are the three remaining dead-end paths.

activity, and participants could pick up a block using a pinching gesture. An offset to the hand's position was applied during some stacking tasks, and participants were asked to identify when an offset was applied [59].

Navigation activity: In this activity, participants were supposed to complete ten trials each time they performed the activity(each session). During each trial, participants were asked to navigate through a maze-like environment (see Section 4.2 for details). As part of the trial, they had to find a key to open a locked door leading to the exit. Upon reaching the exit, participants were asked to point in the direction of where they found the key and where they had begun the trial. Participants were randomly assigned to one of two between-subject conditions in the navigation activity: the teleportation or the joystick-based locomotion condition. They were asked to complete this activity four times, once each week. They did not receive feedback on their performance during experiment implementation to minimize learning impacts. Participants could quit the session at any time due to the risk of cybersickness associated with this activity. The igroup presence and simulator sickness questionnaire were administered for each session; participants completed the Simulator Sickness Questionnaire [57] and the iGroup presence questionnaire [94].

4.5 Results

Linear mixed models (LMMs) analyzed the experiment results and tested the hypotheses. Models were created in R [86] using the 'buildmer' [115] and 'lme4' [6] R packages. Buildmer automatically tests different possible models based on a set of independent variables and uses the model's likelihood-ratio test and the minimum Bayesian information criterion to select the model that best matches the observed data [95]. Fixed effects that are not included in the final model can be assumed to have had little effect on the modeled variable. Once the final model was specified, it was fitted to the data using the lmer command provided

Figure 4.2: An example of a typical room in the different levels.

by lme4. The lmerTest package was used to estimate p-values using the Satterthwaite degrees of freedom method [93] for the models generated by lmer. Figures were generated using ggplot2 [119]. Unless stated otherwise, condition, session, and trial number were input into Buildmer as potential fixed effects when modeling a given independent variable.

Sixteen of our twenty participants completed all four sessions. Of these participants, six were in the joystick condition, and ten were in the teleportation condition. Although we asked participants to complete 10 trials per session, they completed an average of 5.9 trials per session in joystick mode and 8.2 trials per session in teleportation mode. The higher drop rate for the joystick condition can likely be attributed to the increased cybersickness associated with joystick-based locomotion. In total, 141 trials were completed in the joystick condition, and 321 trials were completed in the teleportation condition.

Table 4.1: Parameters of locomotion time model

Parameter	Coefficient [95% CI]	Std. Coef. [95% CI]	t(484)	p
(Intercept)	158.17 [137.54, 178.80]	0.66 [0.36, 0.97]	15.07	< .001
Session	-22.95 [-29.90, -16.01]	-0.43 [-0.57, -0.30]	-6.49	< .001
Condition [Teleportation]	-72.51 [-98.47, -46.54]	-0.94 [-1.33, -0.55]	-5.49	< .001
Session * Condition [Teleportation]	12.10 [3.80, 20.41]	0.23 [0.07, 0.39]	2.86	0.004

4.5.1 Locomotion Time

We fitted a linear mixed model to predict Locomotion Time with Session, Condition, and Session by Condition. The model included PID as a random effect. The model's total explanatory power is substantial

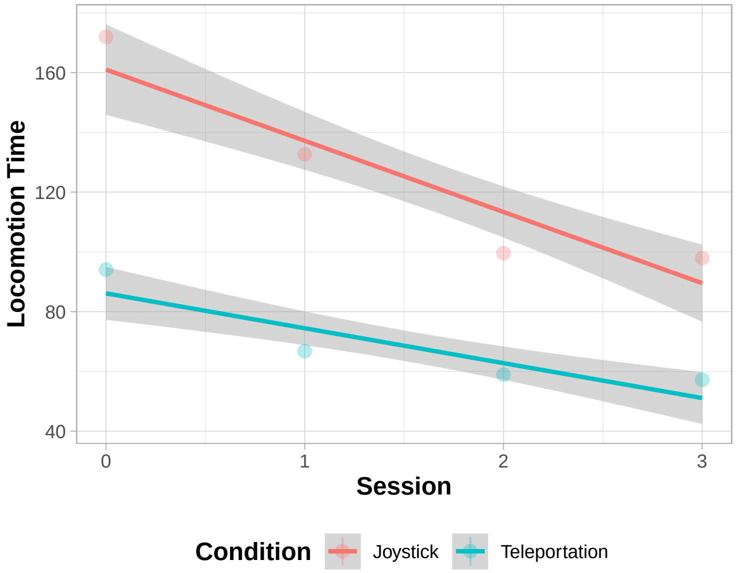

Figure 4.3: The time taken to complete the navigation trials decreased across sessions in both conditions; however, it decreased at a faster rate in the joystick condition.

(conditional $R^2 = 0.39$), and the part related to the fixed effects alone (marginal R^2) is 0.25. The coefficients for the fixed effects are reported in Table 4.1.

The time required to complete a trial decreased by 22.95 seconds for each additional completed session. Additionally, the time taken to complete the trial decreased by 72.51 seconds compared to the joystick when using teleportation. However, the two-way interaction effect between Session and Condition [Teleportation] indicates that the effect of Session was less pronounced for participants who used teleportation, such that the effect of Session decreased by 12.10 seconds when using teleportation.

Table 4.2: Spatial Memory Model Parameters

Parameter	Coefficient [95% CI]	Std. Coef. [95% CI]	t(1079)	p
(Intercept)	33.79 [21.72, 45.85]	-0.20 [-0.50, 0.10]	5.50	< .001
Session	-3.85 [-7.48, -0.21]	0.03 [-0.08, 0.14]	-2.08	0.038
Condition [Teleport]	-0.62 [-15.86, 14.63]	0.35 [-0.03, 0.73]	-0.08	0.937
Trial	-3.45 [-6.04, -0.86]	-0.06 [-0.17, 0.05]	-2.61	0.009
Session * Condition [Teleport]	3.26 [-1.33, 7.84]	-0.08 [-0.21, 0.05]	1.39	0.164
Session * Trial	1.15 [0.26, 2.04]	0.14 [0.03, 0.26]	2.53	0.012
Condition [Teleport] * Trial	3.47 [0.49, 6.44]	0.02 [-0.11, 0.15]	2.29	0.022
(Condition [Teleport] * Trial) * Session	-1.28 [-2.32, -0.25]	-0.16 [-0.29, -0.03]	-2.43	0.015

4.5.2 Spatial Memory

After reaching the end of a trial, participants were asked to point in the direction of where they started the level and where they found the key card. The angular error between the direction they pointed in and the true direction was then calculated. This analysis used an absolute angular error in the horizontal XZ plane, as we do not anticipate any right/left directional effects since the entire level was on a single XZ plane.

We fitted a linear mixed model to predict Absolute Angular Error with Session, Condition, Trial Number, and all interaction effects as fixed effects. The model included PID as a random effect. The model's total explanatory power is moderate (conditional R^2 = 0.15), and the part related to the fixed effects alone (marginal R^2) is 0.03. The coefficients for the fixed effects are reported in Table 4.2.

The baseline error predicted by the model was 33.79°. This error decreased by 3.85° for each additional Session completed and decreased by 3.85° for each additional trial completed.

The effect of Trial on error was moderated by Session, such that the effect of Trial diminished by 1.15° for each additional session completed, indicating that the effect of Trial on error diminished as participants completed more sessions. Similarly, the effect of Trial on error was moderated by Condition, such that the effect of Trial diminished by 3.47° when in the teleportation condition, indicating that Trial had little effect on error when participants moved via teleportation. However, the three-way interaction indicates that the effect of Trial on error became meaningful as the Session increased. The effect of Trial in the teleportation condition decreased error by an additional 1.28° for each additional session completed.

4.5.3 Simulator Sickness

We report separate analyses for each of the four factors of the Simulator Sickness Questionnaire in this section. The questionnaire asks participants to score 16 symptoms on a four-point scale (0-3). A factor analysis revealed that these symptoms could be placed into three general categories: Oculomotor, Disorientation, and Nausea [57]. The total Score represents the overall severity of motion sickness experienced by the users of virtual reality systems.

4.5.3.1 Nausea

We fitted a linear mixed model to predict Nausea with Session and Condition. The model included PID as a random effect. The model's total explanatory power is weak (conditional R^2 = 0.07), and the part related to the fixed effects alone (marginal R^2) is 2.76e-03. The coefficients for the fixed effects are reported in

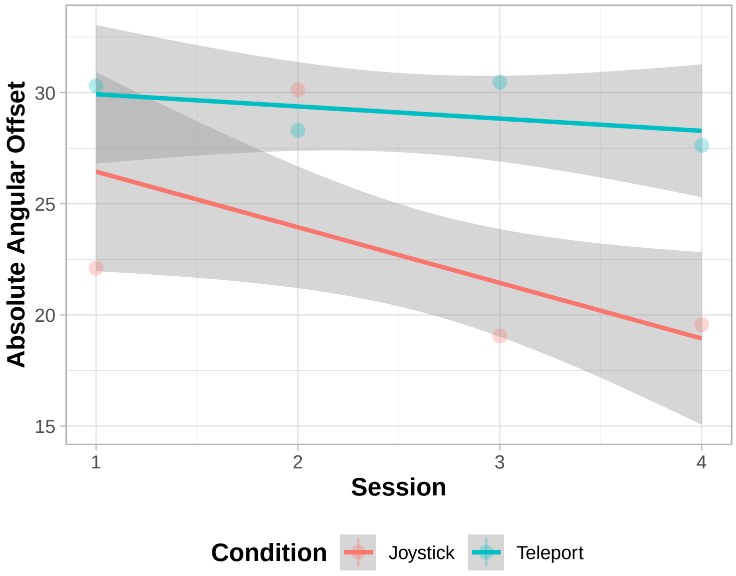

Figure 4.4: Angular error decreased markedly across sessions in the joystick condition but only decreased slightly in the teleportation condition.

Table 4.3. Neither Session nor Condition had a significant effect on Nausea scores.

Table 4.3: Nausea Model Parameters

Parameter	Coefficient [95% CI]	Std. Coef. [95% CI]	t(62)	p
(Intercept)	29.60 [24.21, 34.98]	0.04 [-0.37, 0.45]	10.99	$< .001$
Session	0.27 [-1.52, 2.06]	0.04 [-0.21, 0.28]	0.30	0.762
Condition [Teleportation]	-0.64 [-5.05, 3.78]	-0.08 [-0.62, 0.47]	-0.29	0.773

4.5.3.2 Disorientation

We fitted a linear mixed model to predict Disorientation with Session, Condition, and Session by Condition. The model included PID as a random effect. The model's total explanatory power is moderate (conditional $R^2 = 0.22$), and the part related to the fixed effects alone (marginal R^2) is 0.07. The coefficients for the fixed effects are reported in Table 4.4. Disorientation increased by 1.53 for each additional session that was completed. However, the two-way interaction between Session and Condition [Teleportation] indicates that this increase in disorientation was primarily seen in the Joystick condition, as the effect of Session in the Teleportation condition decreased by 1.98.

Table 4.4: Disorientation Model Parameters

Parameter	Coefficient [95% CI]	Std. Coef. [95% CI]	t(61)	p
(Intercept)	11.71 [7.64, 15.78]	0.13 [-0.31, 0.57]	5.76	$< .001$
Session	1.53 [0.05, 3.00]	0.35 [0.01, 0.69]	2.07	0.043
Condition [Teleportation]	3.65 [-1.79, 9.10]	-0.23 [-0.82, 0.36]	1.34	0.184
Condition [Teleportation] * Session	-1.98 [-3.94, -0.02]	-0.46 [-0.91, 0.00]	-2.02	0.048

4.5.3.3 Oculomotor

We fitted a linear mixed model to predict Oculomotor with Session and Condition. The model included PID as a random effect. The model's total explanatory power is substantial (conditional R^2 = 0.43), and the part related to the fixed effects alone (marginal R^2) is 0.17. The coefficients for the fixed effects are reported in Table 4.5. While Session did not significantly affect Oculomotor discomfort, it did decrease by 10.09 points when using teleportation compared to joystick locomotion.

Table 4.5: Oculomotor Model Parameters

Parameter	Coefficient [95% CI]	Std. Coef. [95% CI]	t(62)	p
(Intercept)	23.99 [15.75, 32.22]	0.44 [-0.03, 0.91]	5.82	$< .001$
Session	-1.96 [-4.27, 0.34]	-0.16 [-0.36, 0.03]	-1.70	0.094
Condition [Teleportation]	-10.09 [-18.39, -1.80]	-0.77 [-1.39, -0.14]	-2.43	0.018

4.5.3.4 Total Sickness Score

We fitted a linear mixed model to predict the Total with Condition. The model included PID as a random effect. The model's total explanatory power is moderate (conditional R^2 = 0.25), and the part related to the fixed effects alone (marginal R^2) is 0.10. The coefficients for the fixed effects are reported in Table 4.6. While Session did not significantly affect Total Sickness, it did decrease by 5.46 points when using teleportation compared to joystick locomotion.

Table 4.6: Total Sickness Score Model Parameters

Parameter	Coefficient [95% CI]	Std. Coef. [95% CI]	t(62)	p
(Intercept)	27.32 [21.55, 33.08]	0.34 [-0.09, 0.78]	9.47	$< .001$
Session	-0.78 [-2.57, 1.01]	-0.10 [-0.31, 0.12]	-0.87	0.386
Condition [Teleportation]	-5.46 [-10.70, -0.23]	-0.61 [-1.19, -0.03]	-2.09	0.041

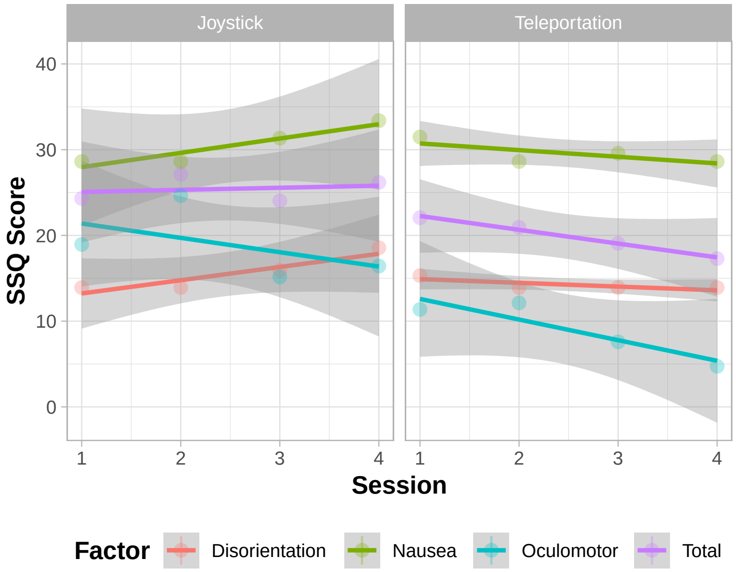

Figure 4.5: While some effects were observed for simulator sickness, reported sickness scores were relatively stable overall.

4.5.4 Presence by Session

Presence as the subjective psychological response in a VR system varies for different users. Participants were asked to answer questions regarding their sense of presence. We have used the igroup Presence Questionnaire (IPQ) [94] as a scale for measuring the sense of presence experienced in a virtual environment. IPQ is developed in three main categories, which make 16 questions with slightly different themes altogether. The 16-item scale evaluated presence in terms of spatial presence, involvement, and judgment of realness.

4.5.4.1 Spatial

We fitted a linear mixed model to predict Spatial with Session. The model included PID as a random effect. The model's total explanatory power is substantial (conditional R^2 = 0.58), and the part related to the fixed effects alone (marginal R^2) is 0.03. The coefficients for the fixed effects are reported in Table 4.7. Spatial presence decreased by 0.17 for each additional session completed.

Table 4.7: Spatial Model Parameters

Parameter	Coefficient [95% CI]	Std. Coef. [95% CI]	t(62)	p
(Intercept)	0.71 [0.19, 1.22]	0.02 [-0.37, 0.40]	2.74	0.008
Session	-0.17 [-0.31, -0.02]	-0.19 [-0.35, -0.02]	-2.24	0.029

4.5.4.2 Involvement

We fitted a linear mixed model to predict Involvement with the Session. The model included PID as a random effect. The model's total explanatory power is substantial (conditional $R^2 = 0.33$), and the part related to the fixed effects alone (marginal R^2) is 0.02. The coefficients for the fixed effects are reported in Table 4.8. The session did not have a significant effect on Involvement.

Table 4.8: Involvement Model Parameters

Parameter	Coefficient [95% CI]	Std. Coef. [95% CI]	t(62)	p
(Intercept)	-0.02 [-0.79, 0.75]	0.02 [-0.32, 0.36]	-0.05	0.963
Session	-0.17 [-0.43, 0.08]	-0.14 [-0.35, 0.07]	-1.35	0.183

4.5.4.3 Realism

We fitted a linear mixed model to predict Realism with the Session. The model included PID as a random effect. The model's total explanatory power is substantial (conditional $R^2 = 0.41$), and the part related to the fixed effects alone (marginal R^2) is 3.77e-04. The coefficients for the fixed effects are reported in Table 4.9. The session did not have a significant effect on Realism.

Table 4.9: Realism Model Parameters

Parameter	Coefficient [95% CI]	Std. Coef. [95% CI]	t(62)	p
(Intercept)	-0.84 [-1.36, -0.32]	0.02 [-0.34, 0.38]	-3.20	0.002
Session	-0.02 [-0.18, 0.15]	-0.02 [-0.22, 0.18]	-0.20	0.842

4.5.4.4 Total Presence Score

We fitted a linear mixed model to predict the Total Score with the Session. The model included PID as a random effect. The model's total explanatory power is substantial (conditional $R^2 = 0.53$), and the part related to the fixed effects alone (marginal R^2) is 0.01. The coefficients for the fixed effects are reported in Table 4.10. The session did not have a significant effect on Total Presence.

Table 4.10: Total Presence Score Model Parameters

Parameter	Coefficient [95% CI]	Std. Coef. [95% CI]	t(62)	p
(Intercept)	-0.01 [-0.43, 0.41]	0.03 [-0.35, 0.41]	-0.07	0.948
Session	-0.09 [-0.21, 0.04]	-0.12 [-0.29, 0.05]	-1.37	0.174

4.6 Discussion

Regarding RQ1, Session was observed to have several effects on participant behavior: participants 1) completed trials an average of 22.63 seconds more quickly for each session they completed ($p < 0.001$), 2) improved their performance on the spatial memory task by an average of 3.85° for each session completed ($p = 0.038$), 3) reported experiencing slightly more disorientation with each session completed ($p = 0.043$), and 4) reported experiencing slightly less spatial presence with each session completed ($p = 0.029$). While simple learning effects likely played a large role in the improvement in trial completion time between sessions, participants' improvement on the spatial memory task is not as easily attributable to a learning effect as participants were not provided with any feedback about their performance on this task. These results show how at least some aspects of navigation and locomotion can change over time as users become more proficient with a locomotion technique.

Regarding RQ2, we observed differences between both locomotion methods, as expected from prior work: participants 1) completed the navigation trials an average of 72 seconds faster when using teleportation and 2) were more accurate on the spatial recall task when using joystick locomotion. However, we also observed interaction effects between the locomotion method and session, indicating that the effect of experience impacted performance on these tasks differently depending on the locomotion method used. Participants improved their completion time more rapidly in the joystick condition than in the teleportation condition. Participants' performance on the spatial memory task improved more rapidly in the joystick condition. While teleportation initially allowed participants to complete the navigation tasks substantially faster, this advantage diminished substantially by the study's conclusion. This highlights how some differences in locomotion methods may diminish over time as users become more familiar with their use. However, a contrasting effect was seen for the locomotion method's effect on performance in the spatial memory task. The gap between locomotion methods widened substantially with time as participants in the joystick condition saw marked improvements while participants in the joystick condition showed little improvement. This shows how differences between locomotion methods can grow more pronounced with time and experience.

A more complex observation can be made regarding the session's effect on spatial memory as expressed in the three-way interaction effect involving the locomotion method, trial number, and session. The main effect of trial ($\mu = -3.45, p = 0.009$) suggests that participants improved their spatial memory within a given session across the 10 trials. However, this effect was moderated by two-way interaction effects with both locomotion method ($\mu = 3.47, p = 0.022$) and session ($\mu = 1.15, p = 0.012$): participants in the teleportation condition showed little improvement across trials within a given session, and the effect of trial diminished as session increased (likely due to an improvement in baseline performance leaving less room for improvement). Finally, a three-way interaction effect was observed for the session on the locomotion method by trial ($\mu = -1.28, p = 0.015$): as the session increased, participants who used teleportation began to improve their performance across trials within a given session. In sum, participants who moved via joystick locomotion were immediately able to improve their performance on the spatial memory task within a given session; in contrast, participants who moved via teleportation were initially unable to improve their performance on the spatial memory task within a given session but learned to do so as session increased. Two implications emerge from these findings: 1) performance gaps between locomotion techniques may widen with time when

The concepts of *calibration* and *attunement* may help to explain why the trial's effect on accuracy was mediated differently between conditions [50] (accuracy was directly mediated by trial in the joystick condition, but the session in the teleportation condition further mediated this effect). Calibration and attunement are both concepts about the role of sensory information in the perception-action system. Calibration occurs when an organism adapts its behavior in response to salient information acquired through its sensory system. On the other hand, attunement is the process by which an organism identifies what information *is* salient to a given activity, which can then be used for calibration. Optic flow is an important source of information regarding self-motion in the real world; its presence when using joystick locomotion and absence when using teleportation is an often cited reason why spatial awareness suffers when using teleportation compared to other continuous forms of locomotion [7]. As users are already familiar with the information provided by optic flow, the steady improvement in spatial awareness observed in participants who used joystick locomotion may manifest their calibrating to the varying properties of optic flow in VR compared to the real world. In contrast, as no optic flow is present when teleporting, this source of information was not available to participants in the teleportation condition to use when calibrating their spatial awareness. Instead, we see a three-way interaction effect whereby participants initially failed to improve their performance across trials in a given session but later gradually improved their performance across trials. This may be a sign that participants in this condition were attuning to other sources of information that could be used for calibration in the absence of optic flow.

Regarding RQ3 and RQ4, the present findings shed light on the anticipated effects of locomotion on sickness in the context of virtual reality experiences. Our study revealed that teleportation exhibited a notable association with reduced feelings of overall sickness ($\mu = -5.46, p = 0.041$) and oculomotor discomfort ($\mu = -10.09, p = 0.018$). These results align with previous expectations and provide empirical evidence supporting the potential benefits of teleportation as a preferred locomotion technique to mitigate sickness symptoms.

The effects of the session were less pronounced on sickness and presence. Feelings of disorientation were reported to increase across sessions ($\mu = 1.53, p = 0.043$), but no effects of the session were observed for the other measured dimensions of simulator sickness. An interaction effect between session and locomotion method on disorientation was also observed where the effect of session on disorientation was diminished for participants who moved via teleportation ($\mu = -1.98, p = 0.048$).

The relation between locomotion methods, sessions, and simulator sickness suggests additional research to explain the underlying factors contributing to these relationships. By advancing our understanding of locomotion effects on sickness, these findings contribute to optimizing virtual reality experiences, enhancing user comfort, and facilitating the development of immersive applications across various domains.

4.7 Limitations

When interpreting these results, it is important to note that participants in the joystick condition completed fewer activities overall and fewer trials within those activities, most likely due to the higher simulator sickness associated with joystick locomotion. As such, the results regarding sickness should be interpreted cautiously, as they may under-report the typical amounts of sickness associated with joystick locomotion. It should also be noted that sickness and presence scores were only collected once for each activity, which means fewer data points existed for our analysis than the data for completion for time and spatial memory, both of which were collected during each trial.

It should also be noted that, as this experiment was conducted in the wild, we did not control for what applications participants used and when they engaged in them. We chose to allow for more naturalistic conditions akin to those real consumers would engage in after acquiring a VR HMD to increase the ecological validity of this experiment. We believed this to be important as real users will likely encounter multiple forms of locomotion simultaneously across different applications.

4.8 Conclusion

The presented results demonstrate that a user's familiarity with a given locomotion technique can influence locomotive behaviors and effects. While not conclusive, it is particularly interesting how the effect of session on completion time was more pronounced in the joystick condition, which performed worse overall than the teleportation condition; similarly, the effect of session on spatial memory, as indicated by the three-way interaction effect, was more pronounced for the teleportation condition, which also performed worse overall than the joystick condition. This may suggest that some of the tradeoffs between locomotion methods may become less meaningful over time as users become more familiar with the technique. Cybersickness was a notable exception to this pattern, as cybersickness generally increased in the joystick condition.

In sum, participants who moved via joystick locomotion were immediately able to improve their performance on the spatial memory task within a given session; in contrast, participants who moved via teleportation were initially unable to improve their performance on the spatial memory task within a given session but learned to do so as session increased. More research is needed to understand how specific behaviors and effects associated with different locomotion techniques are affected when users become more familiar with the technique.

Chapter 5

Longitudinal impact of locomotion methods on spatial awareness in virtual reality and real-world gait after exiting VR

VR researchers have conducted various studies to understand the aftereffects of walking in VR, ranging from visual and cognitive changes to physical symptoms. According to recent studies, users may experience symptoms such as headaches, dizziness, fatigue, and disorientation after using VR, especially in cases where the VR environment is not aligned with the user's physical movements. These symptoms are commonly referred to as simulator sickness or VR sickness. They are thought to be caused by conflicting sensory information and the lack of physical feedback in the VR environment [73, 108]. Research has also explored the impact of VR locomotion on gait parameters and found that there can be changes in walking patterns, balance, and stride length after exposure to VR [55, 76]. These changes are caused by the interaction between the user's body and the VR environment. The extent of these changes may depend on various factors, such as the type of VR locomotion technology used and the duration of exposure.

5.1 Research Design

In this chapter, we present the results of a longitudinal experiment in which participants underwent a locomotion-navigation experiment three times a week. The experiment aimed to investigate the aftereffects of locomotion and navigation in VR. We hypothesized that the experience of walking in a virtual environment would modify their real-world walking patterns after exposure to VR.

The experiment also explored the effects of different locomotion methods on the aftereffects of walking in virtual reality. The study evaluated two distinct techniques: teleportation and joystick-based locomotion. We anticipated that walking in VR would cause some alterations in the participants' sense of presence and simulator sickness. Also, we expected to observe considerable changes in users' gait parameters like speed, step length, body angle, and path deviation in the real world.

As a follow-up to our previous studies [80, 81], this study investigated the possible changes in locomotion and navigation in VR and its aftereffects over the three-session period. We hypothesized that the navigation parameters within VR, such as spatial memory, and the locomotion parameters, such as walking speed in the real world, would be altered after multiple VR sessions. This study aimed to determine how VR locomotion and navigation using the joystick and teleportation techniques modify participants' walking behavior in both VR and the real world over time.

So, a controlled experiment was conducted to investigate the effects of walking in IVEs on novice VR users' walking behavior. First, participants completed 20 trials of natural walking in a real room, during which their gait parameters were collected. Subsequently, participants used the joystick-based or teleportation technique to navigate a virtual environment, specifically a maze-like setting (see Figure 5.2). Ten navigation trials were conducted, during which parameters such as the time required to complete the task and spatial accuracy were recorded. Finally, participants completed another 20 trials of natural walking in the real world to collect their walking behavior after their VR experience. The second real-world situation was identical to the first one to ensure the reliability of the results.

The research questions that this study aimed to answer are as follows:

RQ1: Will participants' locomotive behaviors change in the real world after locomotion in VR?

RQ1-1: Will gait parameters become more pronounced with experience?

RQ1-2: Will the locomotion method impact change in gait parameters in the real world?

RQ2: Will participants' locomotive behaviors change in VR over time?

RQ3: Will the locomotion method impact change in navigation in VR over time?

5.2 Environment and Equipment

5.2.1 Real-world Walking Phases

Participants walked between two targets placed diagonally in our 8x6 m space that is tracked using 4 HTC Vive Lighthouse 2 sensors placed in the corners of the space. Targets were marked on the floor using an X made of masking tape. The tracking space was carefully aligned with the real world prior to each experiment by placing controllers on each of these targets in the real world and aligning the space based on their positions. Data was sampled at 60 hz. Based on the tracked hip, feet, and head, we computed the following gait parameters: 1) walking speed, 2) distance walked, and 3) step count.

Upon examining the data after the experiment, it was discovered that the tracked feet data contained significant artifacts that prevented reliable computation of step metrics. Instead, we extracted step count (or a similar metric) from the changes in the vertical position of the hip tracker. A python program was written to extract this information from the tracked hip data. First, any linear trend in the data was removed to eliminate any inaccuracies in the tracking systems orientation (e.g., the floor was not quite level). The remaining signal was then smoothed with a SciPy's $Savitzky-Golay$ filter with a window size of 11 and a polyorder of 3. These values were determined graphically by observing how well the filtered data matched the original data across a number of different participants. Finally, the Y value of the signal was inverted to convert troughs into peaks and SciPy's $find\_peaks$ function (with a prominence of 0.01) was applied to detect when a trough in the original signal occurred. This was also verified graphically by plotting the identified troughs on the original signal and examining this across multiple participants. The number of observed troughs was then counted, and this was interpreted as the number of steps participants took during a given walking trial.

5.2.2 VR Locomotion Phase

During the VR phase, participants used a Meta Quest Pro, which provides a resolution of 1,920 by 1,800 pixels per eye with a 120-degree field of view and a refresh rate of 90 Hz. The hard hat with the HTC Vive tracker was removed for this phase, but other trackers were left on the participant. Tracking data was not recorded during this phase as participants navigated the virtual environment using artificial locomotion methods due to space constraints.

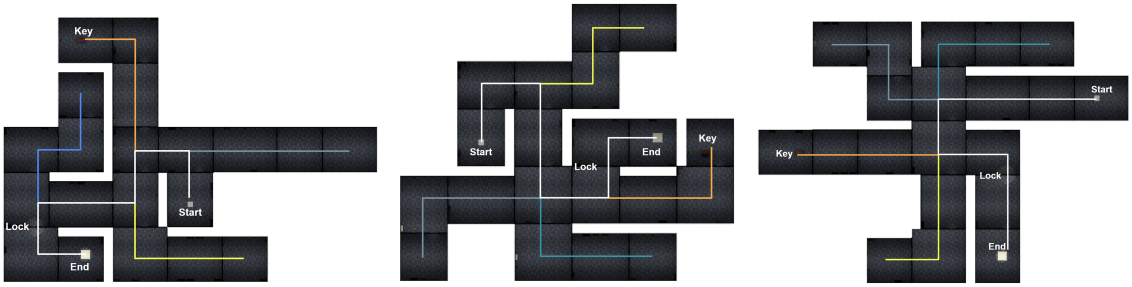

Figure 5.1: Three examples of floorplans in VR environment. In these images, the main path from start to end is shown in white, and the side path to the key is colored green. The other colored paths are the three remaining dead-end paths.

Twenty different floorplans were automatically generated using the Dungeon Architect plugin [111] for the Unity game engine. All floorplans were designed with the following constraints: 1) the main path from start to finish was 8 rooms long, 2) four side paths containing three rooms ending in a dead-end, 3) a key-card was placed at the final room of one of these side paths, 4) a locked door that could be opened with the keycard was placed on the main path after the four side paths. All rooms were directly connected to other rooms; no corridors were in the floorplans. These rules ensured that the different floorplans contained the same number of rooms, the same connectivity, and the shortest path of the same length (crossing through 10 unique doorways, 3 of which were traversed twice). Example floorplans can be seen in Figure 5.1, and an example of a typical room can be seen in Figure 5.2.

Locomotion was implemented using VRTK 4 [1] and the VRTK Prefabs v1.1.8 [36]. Joystick locomotion was calibrated to move participants at a constant speed of 2.25 meters per second, equivalent to a fast walk. Pushing forward on the joystick would translate participants in the direction they were facing; participants could move side-to-side or backward by pushing the joystick in the appropriate direction. A dead zone of 10% was used to prevent very slight adjustments of the joystick from moving participants. Teleportation was implemented where participants pressed down on the trigger to activate a parabolic raycast that could be used to select where they wanted to move to. Once they had indicated where they wanted to move using the raycast, participants released the trigger to teleport to that location. Teleportation occurred instantaneously without any fading of the scene view. The maximum distance participants could teleport at once was 10 meters.

---

[1] https://www.vrtk.io/

5.3 Participants

For this study, The recruitment process was a bit challenging, as it required finding individuals with limited VR experience willing to participate in the experiment multiple times. The experiment was widely advertised on and off campus to find and hire eligible participants. Thirty participants (12 women and 18 men) were recruited, primarily from Clemson University students who received a $60 gift card after finishing the third session. The following criteria qualified them: 1) possessing less than one hour of prior experience with VR and 2) voluntarily committing to attend the experiment regularly throughout three sessions. Of these participants, fifteen were in the joystick condition, and fifteen were in the teleportation condition. However, one of the participants in the group of joystick users withdrew after the first session due to severe simulator sickness.

Figure 5.2: A room in virtual environment

5.4 Procedure

In order to answer our hypotheses, we designed a longitudinal between-subjects study. Participants completed three sessions, each of which was separated by a single day. In these sessions, participants walked in a real environment to establish a baseline, spent time navigating a virtual environment, and then performed the same walking trials in a real environment a second time to determine what, if any, effects their time in VR had on their gait behaviors.

Upon arriving at the lab for the first time, participants were introduced to the experiment's procedure and purpose and were asked to sign a consent form prior to completing a pre-questionnaire collecting demographics and information concerning their prior experience with VR. Once this was done, the participants were outfitted with HTC Vive trackers that were used to collect gait data; trackers were placed on their hips, both feet and their heads (mounted to a hard hat worn during walking trials). The trackers were then calibrated prior to the beginning of the experiment. Participants then completed 20 walking trials in the real world where they walked back and forth between 2 points that were separated by 6 meters. A sound played when participants arrived at their current target, indicating that one trial was complete and another had begun. Participants were instructed to walk at a pace they found comfortable during real-world trials.

Once these trials were completed, participants entered the VR phase of the experiment. In this phase, participants completed up to 10 trials navigating a collection of mazes (see Figure 5.2). In each maze, participants were instructed to find a key card that would open the door to the exit of the maze. Upon reaching the exit, they were instructed to point in the direction they had started the maze, and they had found the keycard. Participants in this phase were divided into two locomotion conditions: 1) teleportation and 2) continuous steering using a joystick. Participants were asked to complete all 10 trials but were allowed to exit this phase early if they began to experience cybersickness. Participants completed the Simulator Sickness Questionnaire [57] prior to exiting the virtual environment.

Finally, participants completed a second set of walking trials in the real-world. The position of the HTC Vive trackers was adjusted if they had shifted during the VR phase and then recalibrated. Participants then completed 20 additional trials as they had done in the first walking phase. These three phases were repeated three times on separate days.

5.5 Results

Linear mixed-effects models were used in our analysis of the data. The Buildmer package was used to identify the original best-fitting model. Theoretical variations of this best-fitting model were then evaluated and compared using AIC, BIC, and R^2 values. In the event of skewed data, we considered models that were fitted against both non-transformed and log-transformed datasets. We note in each section if the log-transformed dataset resulted in an improved fit. In these cases, the model parameters reported in the tables are appropriate for predicting a log-transformed outcome, and the figures have been back-transformed into normal space to aid the interpretation of the model and its effects.

5.5.1 Gait Before and After Navigating in VR and Across Sessions

To determine how participants' real-world gait parameters were influenced by their time spent in VR and if this evolved over time, we fitted linear mixed-effect models for average walking speed, the actual distance participants walked, and the number of steps taken during each trial. We considered the following fixed effects and their respective interaction terms: 1) the session number, 2) the locomotion method used in VR, and 3) the phase (whether the trial took place before or after the VR experience).

5.5.1.1 Average Walking Speed

The final model predicting the log of average walking speed during a trial (in meters/second) incorporated fixed effects for the variables Session, Locomotion, and Phase, along with interaction terms between Locomotion and Phase and between Session and Locomotion, as well as the random effects of individual IDs. The model accounted for a considerable amount of the variability in the data, with a conditional r^2 of 0.398 and a marginal r^2 of 0.025. However, it should be noted that the majority of this variability was explained by the random effects rather than the fixed effects, as indicated by the small marginal r^2.

Fixed effects and their respective 95% confidence intervals are summarized in Table 5.1. Significant main effects for Session and Phase were observed, as well as a significant interaction effect between Locomotion and Phase and Session and Locomotion. These results suggest that both the session number and the phase significantly influence walking speed, and these effects are moderated by the type of locomotion used. The random effect of ID accounted for individual variability among the 29 participants, revealing a variance of 0.0152 and a standard deviation of 0.123.

Table 5.1: Fixed Effects Estimates Predicting $log(AverageSpeed)$

Predictor	Estimate	[95% CI]	Std. Err	t-value	p-value
Intercept	0.0685	[0.0022, 0.1349]	0.0338	2.025	0.0521
Session	0.0254	[0.0148, 0.0362]	0.0054	4.659	< 0.001
Phase (Post)	-0.0808	[-0.0978, -0.0638]	0.0086	-9.309	< 0.001
Locomotion (Teleportation)	-0.0131	[-0.1055, 0.0793]	0.0471	-0.278	0.7831
Phase:Locomotion	0.0699	[0.0465, 0.0933]	0.0119	5.853	< 0.001
Session:Locomotion	-0.0323	[-0.0473, -0.0175]	0.0761	-4.253	< 0.001

All model assumptions were verified and were within acceptable parameters. Five-fold cross-validation confirmed the model generalizes well with a ratio of RMSE to a standard deviation of 0.791. Of the original 2784 data points, 8 were identified as outliers based on standardized residuals and were removed from the analysis. A marginal effects plot further elucidating the impact of the significant predictors is shown in Figure 5.4.

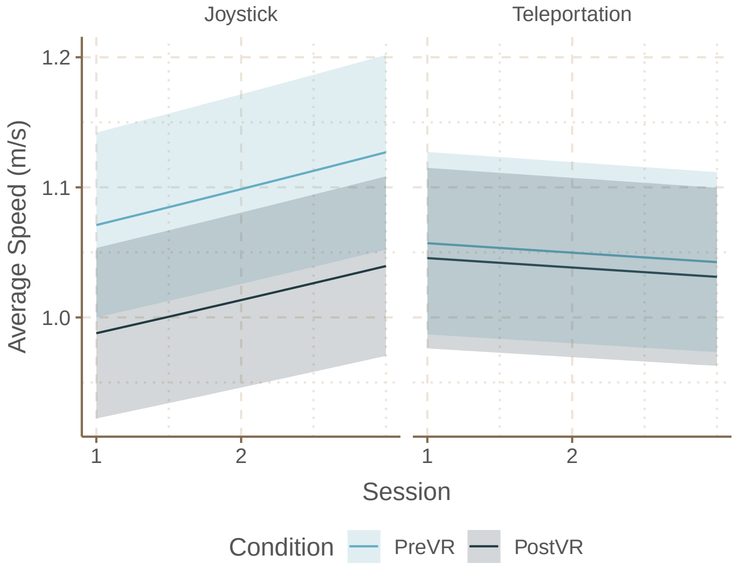

Figure 5.3: Marginal effects showing the relationship between Session, Locomotion, and Phase on Average Walking Speed

5.5.1.2 Distance Walked

The final model predicting the distance participants' walked during a trial (in meters) incorporated fixed effects for the variables Session, Locomotion, and Phase, as well as the random effects of individual IDs. The model accounted for a considerable amount of the variability in the data, with a conditional r^2 of 0.206 and a marginal r^2 of 0.006. However, it should be noted that the majority of this variability was explained by the random effects rather than the fixed effects, as indicated by the small marginal r^2.

Fixed effects and their respective 95% confidence intervals are summarized in Table 5.1. Significant main effects for Session and Phase were observed, as well as a significant interaction effect between Locomotion and Phase and Session and Locomotion. These results suggest that both the session number and the phase significantly influence the distance participants walked during a trial. The random effect of ID accounted for individual variability among the 29 participants, revealing a variance of 0.0808 and a standard deviation of 0.284.

All model assumptions were verified and were within acceptable parameters. Five-fold cross-validation confirmed the model generalizes well with a ratio of RMSE to standard deviation of 0.904. Of the

Table 5.2: Fixed Effects Estimates Predicting Distance Walked

Predictor	Estimate	[95% CI]	Std. Err	t-value	p-value
Intercept	6.943	[6.787, 7.099]	0.0795	87.328	< 0.001
Session	-0.0442	[-0.0716, -0.0169]	0.0139	-3.171	0.00154
Phase (Post)	-0.0604	[-0.1033, -0.0175]	0.0219	-2.762	0.00579
Locomotion (Teleportation)	-0.0030	[-0.2147, 0.2087]	0.1080	-0.028	0.97797

original 2784 data points, 91 were identified as outliers based on standardized residuals and were removed from the analysis. A marginal effects plot further elucidating the impact of the significant predictors is shown in Figure 5.4.

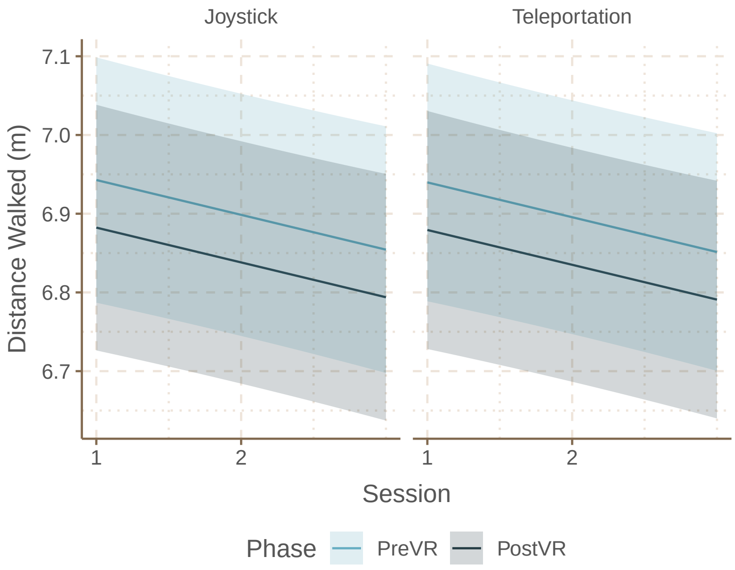

Figure 5.4: Marginal effects showing the relationship between Session, Locomotion, and Phase on the distance walked during a trial.

5.5.1.3 Steps Taken

The final model predicting the number of steps taken during a trial incorporated fixed effects for the variables Session and Condition, along with an interaction term between Session and Condition, as well as random effects of individual IDs and random slopes for Session. The model accounted for a considerable amount of variability in the data, with a conditional r^2 of 0.538 and a marginal r^2 of 0.011. However, it should be noted that the majority of this variability was explained by the random effects rather than the fixed effects, as indicated by the small marginal r^2.

Fixed effects and their respective 95% confidence intervals are summarized in Table 5.3. A significant main effect for Phase was observed, as well as a significant interaction effect between Session and Phase. These results suggest that the phase significantly influences the number of steps taken, and the session number moderates this effect. The random effect of ID accounted for individual variability among the 29 participants, with random effects revealing a variance of 0.9425 for the intercept and 0.2293 for the Session, along with a residual variance of 0.8277.

Table 5.3: Fixed Effects Estimates Predicting Number of Steps

Predictor	Estimate	[95% CI]	Std. Err	t-value	p-value
Intercept	5.887	[5.525, 6.250]	0.185	31.852	< 0.001
Session	-0.00888	[-0.195, 0.177]	0.095	-0.094	0.926
Phase (Post)	0.3686	[0.260, 0.478]	0.056	6.640	< 0.001
Session:Phase (Post)	-0.1776	[-0.264, -0.092]	0.044	-4.048	< 0.001

All model assumptions were verified and were within acceptable parameters. The model generalizes well, as confirmed by a ratio of RMSE to standard deviation of 0.757. Of the original 2693 data points, 145 were identified as outliers based on standardized residuals and were removed from the analysis. Further elucidation of the impact of the significant predictors will be shown in Figure 5.5.

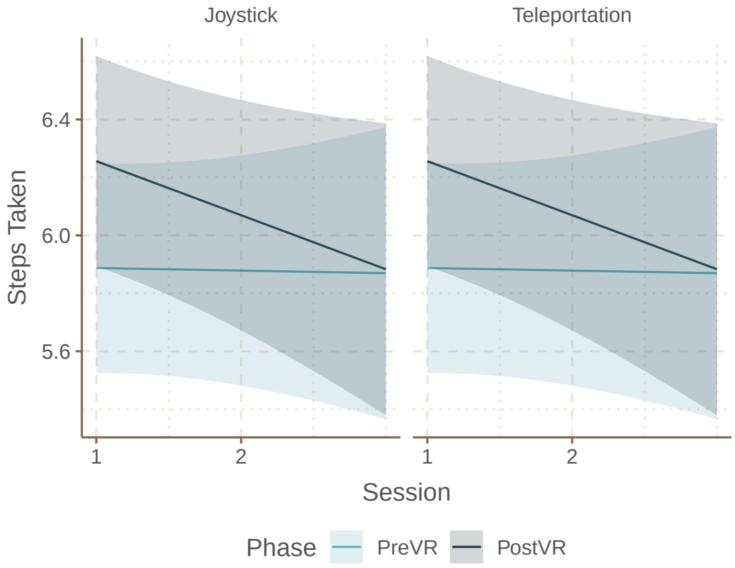

Figure 5.5: Marginal effects showing the relationship between Session, Locomotion, and Phase on the number of steps taken during a trial.

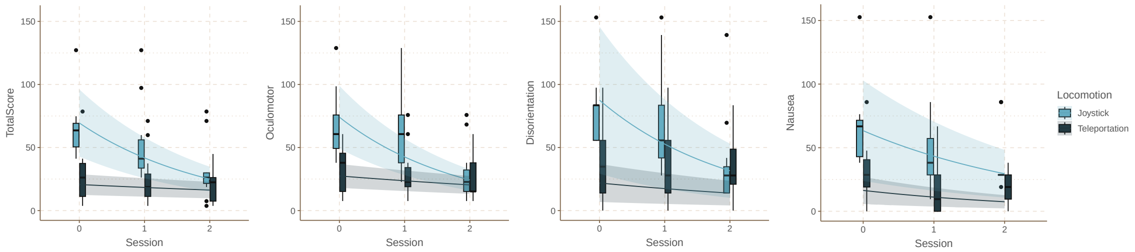

Figure 5.6: All cybersickness factors decreased as additional sessions were completed. This change was most pronounced for participants who used the joystick locomotion method.

5.5.2 Navigation in VR Across Sessions

5.5.2.1 Cybersickness

The final model predicting the log-transformed SSQ scores incorporated fixed effects for the variables Session and Locomotion, along with interaction term between Session and Locomotion, as well as the random effects for individual IDs. The same model structure was used for each of the four SSQ factors: Total Score, Oculomotor, Disorientation, and Nausea. Summary and diagnostic statistics for each model are reported in Table 5.4. The conditional and marginal r^2 were high in all models, suggesting that each model explained a large amount of the variance in the data. All model assumptions were verified and were within acceptable parameters. Five-fold cross-validation confirmed that all models generalize well with ratios of RMSE to standard deviation that were less than 1. A total of 77 SSQ responses were collected from 29 participants across 3 sessions.

Table 5.4: Summary and Diagnostic Statistics for SSQ Models

Model	RE Var.	RE σ	Cond. r^2	Marg. r^2	Outliers	RMSE/σ
Total Score	0.213	0.461	0.624	0.329	3	0.788
Oculomotor	0.211	0.459	0.710	0.326	4	0.836
Disorientation	1.213	1.102	0.867	0.207	6	0.905
Nausea	0.935	0.967	0.817	0.294	6	0.864

Fixed effects and their respective 95% confidence intervals are summarized in Table 5.5. Significant main effects for Session and Locomotion were observed for each SSQ factor, as well as a significant interaction effect between Session and Locomotion for Total Score and for Oculomotor. These results suggest that both the session number and the locomotion method significantly influenced reported sickness scores and that the effect of the session was moderated by the locomotion method for at least some factors.

Table 5.5: Summary of Fixed Effects for log-transformed SSQ Models

Predictor	Estimate	[95% CI]	Std. Err	t-value	p-value
Intercept	4.255	[3.877, 4.633]	0.193	22.078	< 0.001
Session	-0.499	[-0.716, -0.282]	0.111	-4.505	< 0.001
Locomotion (Teleportation)	-1.179	[-1.698, -0.660]	0.265	-4.449	< 0.001
Session:Locomotion	0.385	[0.088, 0.682]	0.152	2.541	0.0144

a) Total Score Model

Predictor	Estimate	[95% CI]	Std. Err	t-value	p-value
Intercept	4.318	[3.987, 4.650]	0.169	25.530	< 0.001
Session	-0.544	[-0.712, -0.377]	0.085	-6.371	< 0.001
Locomotion (Teleportation)	-0.969	[-1.426, -0.512]	0.233	-4.155	< 0.001
Session:Locomotion	0.401	[0.171, 0.630]	0.117	3.425	0.0013

b) Oculomotor Model

Predictor	Estimate	[95% CI]	Std. Err	t-value	p-value
Intercept	4.484	[3.825, 5.142]	0.336	13.350	< 0.001
Session	-0.500	[-0.716, -0.284]	0.110	-4.534	< 0.001
Locomotion (Teleportation)	-1.353	[-2.267, -0.439]	0.466	-2.901	0.0068
Session:Locomotion	0.284	[-0.017, 0.584]	0.153	1.852	0.0709

c) Disorientation Model

Predictor	Estimate	[95% CI]	Std. Err	t-value	p-value
Intercept	4.165	[3.551, 4.778]	0.313	13.307	< 0.001
Session	-0.373	[-0.631, -0.115]	0.132	-2.834	0.0069
Locomotion (Teleportation)	-1.309	[-2.160, -0.457]	0.434	-3.013	0.0048
Session:Locomotion	0.014	[-0.331, 0.360]	0.176	0.082	0.9351

d) Nausea Model

5.5.2.2 Spatial Memory

The final model predicting the log-transformed absolute angular error during pointing tasks after navigating a maze incorporated fixed effects for the variables Session, Locomotion, and Disorientation, along with interaction terms between Session and Locomotion. The model also included nested random effects for individual IDs, Trial Numbers, and Targets within Trials. The model accounted for a notable amount of variability in the data, with a conditional r^2 of 0.359 and a marginal r^2 of 0.076.

Fixed effects and their respective 95% confidence intervals are summarized in Table 5.6. Significant main effects for Session and Disorientation were observed, as well as a significant interaction effect between Session and Locomotion. These results suggest that both the session number and the level of disorientation significantly influenced pointing accuracy, and these effects are moderated by the type of locomotion used.

Of the original 1328 data points, 104 were identified as outliers based on standardized residuals and

Table 5.6: Fixed Effects Estimates Predicting $log(|AngularError|)$

Predictor	Estimate	[95% CI]	Std. Err	t-value	p-value
Intercept	3.977	[3.552, 4.402]	0.217	18.340	< 0.001
Session	-0.353	[-0.474, -0.232]	0.062	-5.714	< 0.001
Locomotion (Teleportation)	0.081	[-0.406, 0.567]	0.248	0.325	0.747
Disorientation	-3.643e-3	[-6.52e-3, -0.76e-3]	0.00147	-2.477	0.0135
Session:Locomotion	0.197	[0.054, 0.340]	0.073	2.697	0.0071

were removed from the analysis. All model assumptions were verified and were within acceptable parameters. The RMSE to standard deviation ratio of 0.8379 indicates that the model has reasonable predictive accuracy for the observed data. A marginal effects plot further elucidating the impact of the significant predictors is shown in Figure 5.7.

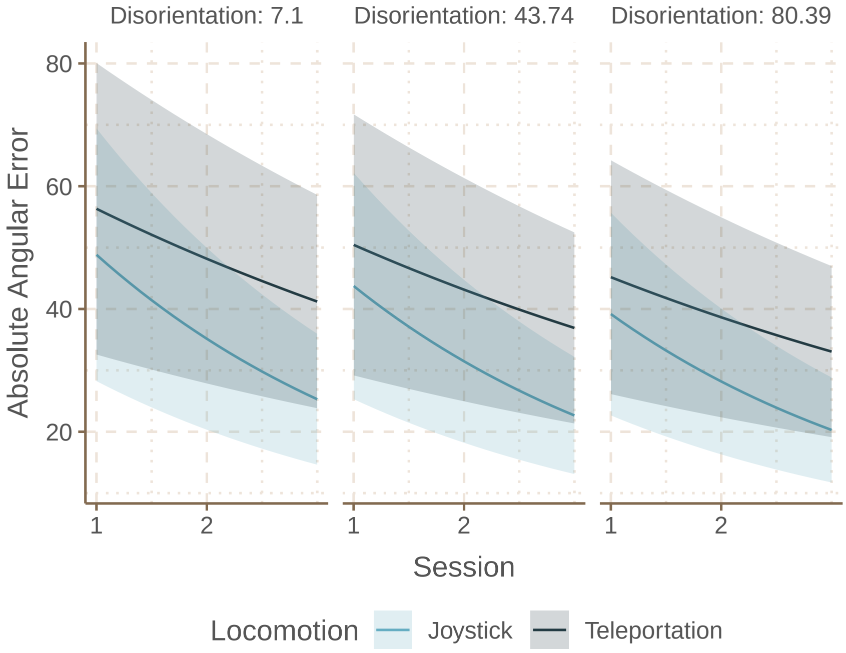

Figure 5.7: Marginal effects showing the relationship between Session, Locomotion, and Disorientation on absolute angular error. The three-way interaction is visualized by showing the two-way effect between Session and Locomotion at different levels of Disorientation (low, medium, high).

5.5.2.3 Trial Completion Time

The final model predicting the log-transformed time taken to complete a trial incorporated fixed effects for the variables Session and Locomotion, along with an interaction term between Session and Locomotion, as

Table 5.7: Fixed Effects Estimates Predicting $log(TimeTaken)$

Predictor	Estimate	[95% CI]	Std. Err	t-value	p-value
Intercept	5.096	[4.949, 5.242]	0.0747	68.184	< 0.001
Session	-0.166	[-0.239, -0.094]	0.0369	-4.504	< 0.001
Locomotion (Teleportation)	-0.227	[-0.425, -0.030]	0.1005	-2.263	0.0284
Session:Locomotion	-0.0759	[-0.173, 0.021]	0.0494	-1.536	0.1250

well as the random effects of individual PIDs. The model accounted for a notable amount of variability in the data, with a conditional r^2 of 0.274 and a marginal r^2 of 0.152. Both the fixed and random effects contributed substantially to explaining the variability in our data, as indicated by the relatively large marginal r^2.

Fixed effects and their respective 95% confidence intervals are summarized in Table 5.7. Significant main effects for Session and Locomotion were observed, but the interaction between Session and Locomotion was not significant. These results suggest that both the session number and the type of locomotion used significantly influence the time taken to complete a trial. The random effect of PID accounted for individual variability among the 29 participants, revealing a variance of 0.0391 and a standard deviation of 0.198.

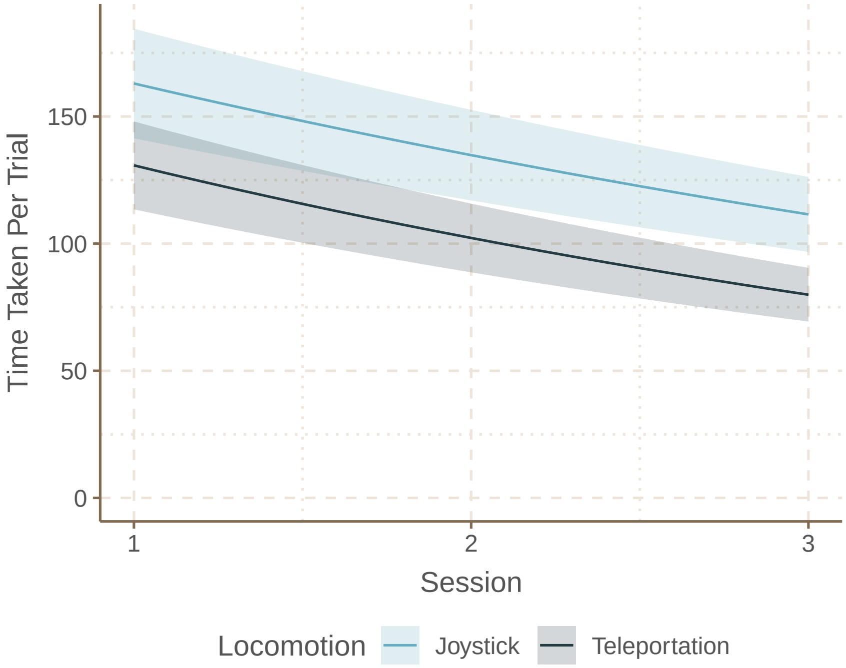

Figure 5.8: Marginal effects showing the relationship between Session and Locomotion on time taken to complete each trial.

Of the original 657 data points, 8 were identified as outliers based on standardized residuals and were excluded from the analysis. All model assumptions were verified and were within acceptable parameters. The model's RMSE to standard deviation ratio was found to be 1.674, exceeding the value of 1. While the RMSE to standard deviation ratio of 1.674 suggests caution in the model's predictive applications, the primary focus of this analysis is on hypothesis testing for the fixed effects. The significant fixed effects are interpreted as unbiased estimates under the assumption that the model is correctly specified. However, the high RMSE to standard deviation ratio indicates that further model refinement may be needed to capture the unexplained variability in the data. A marginal effects plot further elucidating the impact of the significant predictors is shown in Figure 5.8.

5.6 Discussion

5.6.1 Gait in the Real World

All three gait parameters evaluated were impacted by Session: 1) Session directly impacted the average speed and also moderated the effect of Locomotion, 2) Session directly impacted distance walked, and 3) Session moderated the effect of Phase on the number of steps taken. While the effect of Session appeared in all parameters evaluated, all models suggested that the effect size of the fixed effects (including Session) was small (r^2 was smaller than 0.025 in all models). Thus, while virtual reality may affect a user's gait in the real world, this effect is small at the time scale and distances studied in this experiment.

The role of Session as a moderating variable also yielded interesting observations. While not necessarily the case, it would be reasonable to expect behavior measured in the Pre-VR phase to remain consistent across all sessions as users would (presumably) simply exhibit their typical gait parameters. This was observed for the number of steps taken, as Session moderated the effect of Phase such that the number of steps taken remained consistent during the Pre-VR phase but decreased over time in the Post-VR phase (the number of steps taken in this phase started out higher in Session 1), approaching the Pre-VR number of steps by Session 3. A similar effect was observed for average walking speed where Session moderated the effect of Locomotion. In this case, we saw that average walking speed remained relatively unchanged across Sessions when using Teleportation but increased across Sessions when using Joystick locomotion. It is not clear why Session did not moderate Phase for Distance traveled or for Average Speed when using Joystick. This may be indicative of something akin to learning effects where participants became more confident completing the task across Sessions.

Locomotion did not directly impact any of the gait parameters evaluated. However, it did moderate the effect of Phase for average walking speed. Average walking speed decreased in the Post-VR phase compared to the Pre-VR phase. This effect appears to have been more pronounced when using Joystick locomotion. While the data obtained in this experiment is not sufficient to explain this effect, we suspect that it may be due to the difference in optic flow experienced when using Joystick locomotion vs. Teleportation.

Phase impacted all three gait parameters. In each case, the effect of phase suggests that participants were engaged in more cautious gait behavior in Post-VR: participants walked more slowly, took more steps, and covered a shorter distance (indicating a straighter, more direct path). This effect was largely independent of Session except for the number of steps taken. Here Session moderated the effect of the Phase such that the difference between Pre-VR and Post-VR had disappeared by the final Session. This may suggest that participants' gait behavior was more confident in the final Session after exiting VR; however, this should be interpreted cautiously given that this effect was only observed in a single metric.

5.6.2 Locomotion in VR

Session was again observed to effect all measures in VR: simulator sickness, angular error, and trial completion time. Encouraging, while participants in the joystick condition experienced high levels of sickness in the first session, this declined until it was roughly equal to the much lower level of sickness experienced by teleportation participants. Session moderated the effect of locomotion on angular error, such that participants in the Joystick condition improved their performance more across sessions than participants in the Teleportation condition did (however, participants in both conditions improved across Session). The effect of Session on trial completion time may indicate an increased level of comfort with the assigned locomotion system as participants gained experience. Unfortunately the data collected in this experiment is not sufficient to test this hypothesis. It may also represent a learning effect, however it is highly unlikely that it represents an effect of participants learning the individual mazes themselves due to the homogeneity between mazes and the low rate of maze repetition (no more than twice across all sessions). Thus, any learning effect is most likely associated with the procedure and the locomotion method.

Locomotion also affected all measures recorded in VR, either directly as a main effect or by moderating the effect of Session. Participants reported higher levels of sickness when using Joystick locomotion, as expected from prior work. Locomotion also affected spatial memory, however this manifested as by moderating the effect of Session on angular error. Angular error was always lower in the Joystick condition, however, the errors in the first session were relatively close to each other. This gap had widened substantially by the final session. This effect also aligns with prior work showing that continuous forms of locomotion generally result in improved spatial understanding. Locomotion also affected trial completion time, where participants who used teleportation completed the trials faster. This is unsurprising given the affordances of teleportation compared to joystick locomotion.

Finally, we tested the Disorientation simulator sickness factor for inclusion in the model predicting angular error as feelings of disorientation are directly linked to spatial understanding or awareness. While disorientation did have a significant effect on spatial memory, higher levels of disorientation actually served to *reduce* angular error. This effect may have emerged due to behavioral changes produced by increased feelings of disorientation; it may be that participants who felt more disoriented began paying more conscious attention to their environment and thus generated stronger spatial encodings of each maze.

5.7 Conclusion

In conclusion, this research has contributed significantly to our understanding of the effects of locomotion and navigation in virtual reality (VR) on participants' real-world behaviors and the impact of different locomotion methods. Through a meticulous longitudinal experiment, we observed that exposure to VR locomotion does indeed have lasting effects on participants' walking patterns in the real world. Notably, the choice of locomotion method, whether joystick-based or teleportation, influenced these effects, like the joystick leading to slower walking after exiting VR. We also found that VR-induced cybersickness decreased over time, with joystick locomotion initially causing more discomfort. Additionally, trial completion time and spatial awareness were influenced by both session and locomotion methods, like teleportation being associated with shorter completion times. These findings underscore the complex interplay between locomotion and navigation in VR, real-world gait parameters, and simulator sickness, highlighting the need for further research in this emerging field. Overall, this study provides valuable insights into the potential consequences of VR experiences on gait behavior and the nuanced differences between locomotion methods, paving the way for future investigations and applications in virtual reality.

Chapter 6

Conclusions and Discussion

The present dissertation explored the critical aspect of locomotion in Virtual Reality and its influence on users' gait patterns in both the virtual and real worlds. Through three studies, we investigated various facets of VR locomotion, navigation, and users' prior experience with VR effects on them. Also, research was performed to understand the differences and similarities in gait between VR and the real world and the potential changes in gait over time as users become more accustomed to walking in VR.

Study 1 highlighted the importance of considering users' expertise in Virtual Environments when designing locomotion assets. We found significant differences in gait parameters between novices and experts while walking in real and virtual conditions. This emphasizes the need to tailor locomotion techniques to accommodate users' varying experience levels, ultimately enhancing their overall VR experience.

Study 2 involved a longitudinal experiment exploring participants' locomotive performance changes over four weeks. We observed that locomotion methods, such as teleportation and joystick-based locomotion, influenced users' performance in VR over time. Understanding these changes is crucial for designing practical VR applications such as training programs and rehabilitation protocols. Then, Study 3 investigated the aftereffects of VR locomotion on users' gait in the real world. We observed alterations in gait parameters like walking speed, suggesting that VR locomotion experiences impact real-world walking behavior. This finding has implications for various applications, including training and game design.

Overall, this dissertation contributes to understanding how VR locomotion and navigation affect users' gait patterns in both VR and the real world. By exploring the coupling of locomotion and navigation, we gain insights into how VR experiences influence users' spatial understanding and sense of presence. Our findings highlight the significance of adapting VR locomotion techniques to users' expertise levels and designing immersive VR experiences that align with users' real-world walking dynamics. As VR continues to revolutionize various sectors, the knowledge gained from this research can inform the development of more effective and engaging virtual experiences with broad applications in healthcare, education, and entertainment. The investigation of gait in VR and its relationship with users' navigation skills paves the way for future research and advancements in Virtual Reality.

The three conducted studies in this dissertation provide valuable insights into the relationship between gait parameters, VR locomotion, and navigation over time with improved VR experience. The studies aim to understand how locomotion techniques in virtual reality environments impact participants' locomotive behaviors, spatial memory, and simulator sickness. By investigating these aspects, the research contributes to the design of more user-friendly and immersive VR experiences.

Study 1 focused on comparing the gait of inexperienced and experienced VR users in both the real world and virtual reality. The study sought to understand whether prior VR experience influenced locomotive behaviors. Participants were divided into two groups: novices with little to no VR experience and experts with substantial prior VR experience. They were asked to walk in controlled environments in both real and virtual conditions while their gait parameters were measured.

The findings from Study 1 revealed significant differences in walking behavior between novices and experts. Experienced VR users exhibited faster walking speeds and longer step lengths in the virtual environment compared to the novices. This suggests that prior VR experience can influence locomotion in virtual reality, leading to more efficient and comfortable walking patterns. The study emphasized the importance of considering users' expertise in VR environments when designing locomotion assets to provide effective support for both experienced and inexperienced users.

Assessing user experience in locomotion applications can benefit the design or update of VR applications based on the users' experiences, capabilities, and needs. It can help with the more naturalness of users' walking in IVEs and improve user interactions in VR. We compared gait parameters, including speed, step length, and trunk angle, in VR and the real world. The gait characteristics for two conditions and two classes of users were analyzed to assess the effect of the prior VR experience. The more people experience VR, their walking parameters differ in VR and the real room. Our findings demonstrate that the VR experience may make users self-calibrate and distinguish actions in the two conditions.

Building on the insights from Study 1, Study 2 focused on examining changes in navigation behaviors and spatial understanding over time using two locomotion techniques: joystick-based locomotion and teleportation. Participants engaged in a navigation activity four times over four weeks. They were randomly assigned to one of the two locomotion conditions.

The results of Study 2 demonstrated interesting patterns of change in locomotion and navigation behaviors over time. Participants' locomotive performance improved as they became more familiar with the VR environment, regardless of the locomotion technique used. However, the effect of the session on completion time and spatial memory was more pronounced for participants using teleportation as their locomotion method. This suggests that teleportation may offer advantages in terms of adaptability and spatial memory retention in the long term.

Also, the results presented demonstrate that a user's familiarity with a given locomotion technique can influence locomotive behaviors and effects. It is particularly interesting how the effect of the session on completion time was more pronounced in the joystick condition. Similarly, the effect of the session on spatial memory was more pronounced for the teleportation condition. Cybersickness was a notable exception to this pattern, as cybersickness generally increased in the joystick condition. More research is needed to understand better how specific behaviors and effects associated with different locomotion techniques are affected when users become more familiar with the method.

Furthermore, Study 2 explored the effects of locomotion methods on simulator sickness and presence over time. The findings showed that cybersickness generally increased in the joystick condition, while teleportation was associated with lower levels of simulator sickness. This indicates that the choice of locomotion technique can impact users' comfort and well-being during VR experiences.

Study 3 built upon the findings from the previous studies and investigated how walking in VR affects participants' real-world gait parameters over a three-session period. Participants completed natural walking trials in a real room, followed by navigation in a virtual maze-like setting using either joystick-based or teleportation locomotion. Finally, participants completed more natural walking trials in the real world.

In this study, through a meticulous longitudinal experiment, we observed that exposure to VR locomotion does indeed have lasting effects on participants' walking patterns in the real world. Notably, the choice of locomotion method, whether joystick-based or teleportation, influenced these effects, like the joystick leading to slower walking after exiting VR. We also found that VR-induced cybersickness decreased over time, with joystick locomotion initially causing more discomfort. Additionally, trial completion time and spatial awareness were influenced by both session and locomotion methods, like teleportation being associated with shorter completion times. These findings underscore the complex interplay between locomotion and navigation in VR, real-world gait parameters, and simulator sickness, highlighting the need for further research in this emerging field.

The overall findings from the three studies underscore the importance of considering locomotion techniques in VR design. Teleportation emerges as a promising locomotion method, offering advantages in reducing simulator sickness, improving spatial memory, and providing a more comfortable VR experience. The studies also reveal the presence of a learning effect in VR, where participants' walking behaviors and spatial memory improved over sessions.

The link between the three studies lies in their collective focus on understanding the effects of locomotion techniques on locomotion behaviors, spatial memory, and simulator sickness in VR environments. Each study contributes a unique perspective to this exploration, with Study 1 establishing the influence of prior VR experience on gait parameters, Study 2 investigating changes in navigation behaviors over time, and Study 3 examining the lasting effects of VR locomotion on real-world walking parameters. The findings from these studies have several practical implications for the design of VR applications. By understanding how locomotion techniques and VR experience influence user behaviors and outcomes, developers and designers can create VR experiences that fit users' needs and preferences. For example, using teleportation as a locomotion technique may be beneficial for reducing simulator sickness and improving spatial memory, especially with repeated exposure. Additionally, the studies highlight the importance of considering users' expertise in VR environments to provide tailored locomotion support.

However, it is important to acknowledge the limitations of the studies. The sample sizes were relatively small, limiting the generalizability of the findings. Future research with larger and more diverse participant groups is needed to validate and expand upon these results. Additionally, while the longitudinal design provides insights into changes over time, it may not fully capture the long-term effects of VR experience on locomotion behaviors.

In conclusion, the three conducted studies in this dissertation contribute valuable insights into the link between gait parameters, VR locomotion, and navigation over time with increased VR experience. The research provides a foundation for designing more user-friendly and immersive VR experiences by understanding the impact of locomotion techniques on locomotive behaviors, spatial memory, and simulator sickness in VR environments. The findings offer practical implications for VR application development and pave the way for further exploration in this evolving field.

Bibliography

[1] M. Al-Amri, Hilal Al Balushi, and A. Mashabi. Intra-rater repeatability of gait parameters in healthy adults during self-paced treadmill-based virtual reality walking. *Computer Methods in Biomechanics and Biomedical Engineering*, 21(1):41–48, 2017.

[2] Mina Ardekani and Mehmet Şalgamcıoğlu. Design for impact: Studying the role of design in spatial cognition of children with autism.

[3] Marios N Avraamides and Jonathan W Kelly. Multiple systems of spatial memory and action. *Cognitive processing*, 9:93–106, 2008.

[4] Jeremy N Bailenson and Nick Yee. A longitudinal study of task performance, head movements, subjective report, simulator sickness, and transformed social interaction in collaborative virtual environments. *Presence: Teleoperators and Virtual Environments*, 15(6):699–716, 2006.

[5] Woodrow Barfield and Claudia Hendrix. The effect of update rate on the sense of presence within virtual environments. *Virtual Reality*, 1:3–15, 1995.

[6] Douglas Bates, Martin Mächler, Ben Bolker, and Steve Walker. Fitting linear mixed-effects models using lme4. *Journal of Statistical Software*, 67(1):1–48, 2015.

[7] Jiwan Bhandari, Paul R MacNeilage, and Eelke Folmer. Teleportation without spatial disorientation using optical flow cues. In *Graphics interface*, pages 162–167, 2018.

[8] Emilia Biffi, Elena Beretta, Ambra Cesareo, Cristina Maghini, Anna C Turconi, Gianluigi Reni, and Sandra Strazzer. An immersive virtual reality platform to enhance walking ability of children with acquired brain injuries. *Methods of information in medicine*, 56(02):119–126, 2017.

[9] Frank Biocca, Chad Harms, and Judee K Burgoon. Toward a more robust theory and measure of social presence: Review and suggested criteria. *Presence: Teleoperators & virtual environments*, 12(5):456–480, 2003.

[10] Costas Boletsis. The new era of virtual reality locomotion: A systematic literature review of techniques and a proposed typology. *Multimodal Technologies and Interaction*, 1(4):24, 2017.

[11] Costas Boletsis. The new era of virtual reality locomotion: A systematic literature review of techniques and a proposed typology. *Multimodal Technologies and Interaction*, 1(4):24, 2017.

[12] Costas Boletsis and Jarl Erik Cedergren. Vr locomotion in the new era of virtual reality: an empirical comparison of prevalent techniques. *Advances in Human-Computer Interaction*, 2019, 2019.

[13] Doug A. Bowman. *3D user interfaces: Theory and practice*. Addison-Wesley, 2004.

[14] Doug A Bowman, Elizabeth T Davis, Larry F Hodges, and Albert N Badre. Maintaining spatial orientation during travel in an immersive virtual environment. *Presence*, 8(6):618–631, 1999.

[15] Doug A Bowman, David Koller, and Larry F Hodges. Travel in immersive virtual environments: An evaluation of viewpoint motion control techniques. In *Proceedings of IEEE 1997 Annual International Symposium on Virtual Reality*, pages 45–52. IEEE, 1997.

[16] Doug A Bowman, David Koller, and Larry F Hodges. A methodology for the evaluation of travel techniques for immersive virtual environments. *Virtual reality*, 3(2):120–131, 1998.

[17] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. Point & teleport locomotion technique for virtual reality. In *Proceedings of the 2016 annual symposium on computer-human interaction in play*, pages 205–216, 2016.

[18] Stefano Burigat and Luca Chittaro. Navigation in 3d virtual environments: Effects of user experience and location-pointing navigation aids. *International Journal of Human-Computer Studies*, 65(11):945–958, 2007.

[19] Andrea Canessa, Paolo Casu, Fabio Solari, and Manuela Chessa. Comparing real walking in immersive virtual reality and in physical world using gait analysis. In *VISIGRAPP (2: HUCAPP)*, pages 121–128, 2019.

[20] Colleen G Canning, Natalie E Allen, Evelien Nackaerts, Serene S Paul, Alice Nieuwboer, and Moran Gilat. Virtual reality in research and rehabilitation of gait and balance in parkinson disease. *Nature Reviews Neurology*, 16(8):409–425, 2020.

[21] Eunhee Chang, Hyun Taek Kim, and Byounghyun Yoo. Virtual reality sickness: a review of causes and measurements. *International Journal of Human–Computer Interaction*, 36(17):1658–1682, 2020.

[22] Weiya Chen, Anthony Plancoulaine, Nicolas Férey, Damien Touraine, Julien Nelson, and Patrick Bourdot. 6dof navigation in virtual worlds: comparison of joystick-based and head-controlled paradigms. In *Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology*, pages 111–114, 2013.

[23] Yi Chen, Qiang Gao, Cheng-Qi He, and Rong Bian. Effect of virtual reality on balance in individuals with parkinson disease: a systematic review and meta-analysis of randomized controlled trials. *Physical therapy*, 100(6):933–945, 2020.

[24] Heni Cherni, Natacha Métayer, and Nicolas Souliman. Literature review of locomotion techniques in virtual reality. *Int. J. Virtual Real.*, 20:1–20, 2020.

[25] Benjamin Chihak, Herbert Pick Jr, Jodie Plumert, Christine Ziemer, Sabarish Babu, James Cremer, and Joseph Kearney. Optic flow and physical effort as cues for the perception of the rate of self-produced motion in ve. In *Proceedings of the 6th Symposium on Applied Perception in Graphics and Visualization*, pages 132–132, 2009.

[26] Benjamin J Chihak, Jodie M Plumert, Christine J Ziemer, Sabarish Babu, Timofey Grechkin, James F Cremer, and Joseph K Kearney. Synchronizing self and object movement: how child and adult cyclists intercept moving gaps in a virtual environment. *Journal of experimental psychology: human perception and performance*, 36(6):1535, 2010.

[27] Noah Coomer, Sadler Bullard, William Clinton, and Betsy Williams-Sanders. Evaluating the effects of four vr locomotion methods: joystick, arm-cycling, point-tugging, and teleporting. In *Proceedings of the 15th ACM symposium on applied perception*, pages 1–8, 2018.

[28] Natalia Cooper, Ferdinando Millela, Iain Cant, Mark D White, and Georg Meyer. Transfer of training—virtual reality training with augmented multisensory cues improves user experience during training and task performance in the real world. *PloS one*, 16(3):e0248225, 2021.

[29] James J Cummings and Jeremy N Bailenson. How immersive is enough? a meta-analysis of the effect of immersive technology on user presence. *Media psychology*, 19(2):272–309, 2016.

[30] Rudolph P Darken and John L Sibert. Navigating large virtual spaces. *International Journal of Human-Computer Interaction*, 8(1):49–71, 1996.

[31] Rudolph P Darken and John L Sibert. Wayfinding strategies and behaviors in large virtual worlds. In *Proceedings of the SIGCHI conference on Human factors in computing systems*, pages 142–149, 1996.

[32] Laurens De Gauquier, Malaika Brengman, Kim Willems, and Helena Van Kerrebroeck. Leveraging advertising to a higher dimension: experimental research on the impact of virtual reality on brand personality impressions. *Virtual Reality*, 23:235–253, 2019.

[33] Ilona JM De Rooij, Ingrid GL Van De Port, and Jan-Willem G Meijer. Effect of virtual reality training on balance and gait ability in patients with stroke: systematic review and meta-analysis. *Physical therapy*, 96(12):1905–1918, 2016.

[34] Ilona JM de Rooij, Ingrid GL van de Port, Michiel Punt, Pim JM Abbink-van Moorsel, Michiel Kortsmit, Ruben PA van Eijk, Johanna MA Visser-Meily, and Jan-Willem G Meijer. Effect of virtual reality gait training on participation in survivors of subacute stroke: a randomized controlled trial. *Physical therapy*, 101(5):pzab051, 2021.

[35] John V Draper, David B Kaber, and John M Usher. Telepresence. *Human factors*, 40(3):354–375, 1998.

[36] ExtendRealityLtd. Extendrealityltd/vrtk.prefabs: *deprecated* - a collection of productive prefabs for rapidly building spatial computing solutions in the unity software.

[37] Ajoy S Fernandes and Steven K Feiner. Combating VR sickness through subtle dynamic field-of-view modification. In *2016 IEEE symposium on 3D user interfaces (3DUI)*, pages 201–210. IEEE, 2016.

[38] Andrea Ferracani, Daniele Pezzatini, Jacopo Bianchini, Gianmarco Biscini, and Alberto Del Bimbo. Locomotion by natural gestures for immersive virtual environments. In *Proceedings of the 1st international workshop on multimedia alternate realities*, pages 21–24, 2016.

[39] Kathleen E Finn. *Video-mediated communication*. L. Erlbaum Associates Inc., 1997.

[40] Sebastian Freitag, Benjamin Weyers, and Torsten W Kuhlen. Examining rotation gain in cave-like virtual environments. *IEEE transactions on visualization and computer graphics*, 22(4):1462–1471, 2016.

[41] Andreas Frey, Johannes Hartig, André Ketzel, Axel Zinkernagel, and Helfried Moosbrugger. The use of virtual environments based on a modification of the computer game quake iii arena® in psychological experimenting. *Computers in Human Behavior*, 23(4):2026–2039, 2007.

[42] Duncan R Godden and Alan D Baddeley. Context-dependent memory in two natural environments: On land and underwater. *British Journal of psychology*, 66(3):325–331, 1975.

[43] Simone Grassini and Karin Laumann. Questionnaire measures and physiological correlates of presence: A systematic review. *Frontiers in psychology*, 11:349, 2020.

[44] MP Jacob Habgood, David Moore, David Wilson, and Sergio Alapont. Rapid, continuous movement between nodes as an accessible virtual reality locomotion technique. In *2018 IEEE conference on virtual reality and 3D user interfaces (VR)*, pages 371–378. IEEE, 2018.

[45] Kelly S Hale and Kay M Stanney. *Handbook of virtual environments: Design, implementation, and applications*. CRC Press, 2014.

[46] Kelly S. Hale and Kay M. Stanney. *Handbook of Virtual Environments: Design, implementation, and applications, Second edition*. CRC Press, 2014.

[47] John H. Hollman, Robert H. Brey, Tami J. Bang, and Kenton R. Kaufman. Does walking in a virtual environment induce unstable gait?: An examination of vertical ground reaction forces. *Gait Posture*, 26(2):289–294, 2007.

[48] John H Hollman, Robert H Brey, Richard A Robb, Tami J Bang, and Kenton R Kaufman. Spatiotemporal gait deviations in a virtual reality environment. *Gait & posture*, 23(4):441–444, 2006.

[49] Sungjae Hwang, Peter Agada, Stephen Grill, Tim Kiemel, and John J Jeka. A central processing sensory deficit with parkinson's disease. *Experimental brain research*, 234(8):2369–2379, 2016.

[50] David M Jacobs and Claire F Michaels. Lateral interception i: operative optical variables, attunement, and calibration. *Journal of Experimental Psychology: Human Perception and Performance*, 32(2):443, 2006.

[51] Beverly K Jaeger and Ronald R Mourant. Comparison of simulator sickness using static and dynamic walking simulators. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting*, volume 45, pages 1896–1900. SAGE Publications Sage CA: Los Angeles, CA, 2001.

[52] Omar Janeh, Gerd Bruder, Frank Steinicke, Alessandro Gulberti, and Monika Poetter-Nerger. Analyses of gait parameters of younger and older adults during (non-) isometric virtual walking. *IEEE transactions on visualization and computer graphics*, 24(10):2663–2674, 2017.

[53] Samleo L Joseph, Xiaochen Zhang, Ivan Dryanovski, Jizhong Xiao, Chucai Yi, and YingLi Tian. Semantic indoor navigation with a blind-user-oriented augmented reality. In *2013 IEEE International Conference on Systems, Man, and Cybernetics*, pages 3585–3591. IEEE, 2013.

[54] Michal Kafri, Patrice L Weiss, Gabriel Zeilig, Moshe Bondi, Ilanit Baum-Cohen, and Rachel Kizony. Performance in complex life situations: effects of age, cognition, and walking speed in virtual versus real life environments. *Journal of neuroengineering and rehabilitation*, 18(1):1–9, 2021.

[55] Dimitrios Kastavelis, Mukul Mukherjee, Leslie M Decker, and Nikolaos Stergiou. The effect of virtual reality on gait variability. 2010.

[56] Robert S Kennedy, Julie M Drexler, Daniel E Compton, Kay M Stanney, D Susan Lanham, Deborah L Harm, et al. Configural scoring of simulator sickness, cybersickness and space adaptation syndrome: Similarities and differences. *Virtual and adaptive environments: Applications, implications, and human performance issues*, 247, 2003.

[57] Robert S Kennedy, Norman E Lane, Kevin S Berbaum, and Michael G Lilienthal. Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *The international journal of aviation psychology*, 3(3):203–220, 1993.

[58] Aram Kim, Nora Darakjian, and James M Finley. Walking in fully immersive virtual environments: an evaluation of potential adverse effects in older adults and individuals with parkinson's disease. *Journal of neuroengineering and rehabilitation*, 14(1):1–12, 2017.

[59] Kristopher Kohm, John Porter, and Andrew Robb. Sensitivity to hand offsets and related behavior in virtual environments over time. *ACM Transactions on Applied Perception*, 19(4):1–15, 2022.

[60] Eugenia M Kolasinski. Simulator sickness in virtual environments. 1995.

[61] Eric Krokos, Catherine Plaisant, and Amitabh Varshney. Virtual memory palaces: immersion aids recall. *Virtual reality*, 23:1–15, 2019.

[62] Eike Langbehn, Paul Lubos, and Frank Steinicke. Evaluation of locomotion techniques for room-scale vr: Joystick, teleportation, and redirected walking. In *Proceedings of the Virtual Reality International Conference-Laval Virtual*, pages 1–9, 2018.

[63] Florian Larrue, Hélène Sauzéon, Lioubov Aguilova, Fabien Lotte, Martin Hachet, and Bernard NKaoua. Brain computer interface vs walking interface in vr: the impact of motor activity on spatial transfer. In *Proceedings of the 18th ACM symposium on Virtual reality software and technology*, pages 113–120, 2012.

[64] Kung Wong Lau and Pui Yuen Lee. Shopping in virtual reality: a study on consumers' shopping experience in a stereoscopic virtual reality. *Virtual Reality*, 23(3):255–268, 2019.

[65] Jing Lin, Lijun Cao, and Nan Li. Assessing the influence of repeated exposures and mental stress on human wayfinding performance in indoor environments using virtual reality technology. *Advanced Engineering Informatics*, 39:53–61, 2019.

[66] Matthew Lombard, Theresa B Ditton, and Lisa Weinstein. Measuring presence: the temple presence inventory. In *Proceedings of the 12th annual international workshop on presence*, pages 1–15, 2009.

[67] Tamas Madl, Ke Chen, Daniela Montaldi, and Robert Trappl. Computational cognitive models of spatial memory in navigation space: A review. *Neural Networks*, 65:18–43, 2015.

[68] M Rasel Mahmud, Michael Stewart, Alberto Cordova, and John Quarles. Auditory feedback to make walking in virtual reality more accessible. In *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 847–856. IEEE, 2022.

[69] Arthur Maneuvrier, Leslie Marion Decker, Hadrien Ceyte, Philippe Fleury, and Patrice Renaud. Presence promotes performance on a virtual spatial cognition task: Impact of human factors on virtual reality assessment. *Frontiers in Virtual Reality*, 1:571713, 2020.

[70] Dario Martelli, Boxi Xia, Antonio Prado, and Sunil K Agrawal. Gait adaptations during overground walking and multidirectional oscillations of the visual field in a virtual reality headset. *Gait & posture*, 67:251–256, 2019.

[71] Philipp Maruhn, Sonja Schneider, and Klaus Bengler. Measuring egocentric distance perception in virtual reality: Influence of methodologies, locomotion and translation gains. *PloS one*, 14(10):e0224651, 2019.

[72] Marta Matamala-Gomez, Antonella Maselli, Clelia Malighetti, Olivia Realdon, Fabrizia Mantovani, and Giuseppe Riva. Virtual body ownership illusions for mental health: a narrative review. *Journal of Clinical Medicine*, 10(1):139, 2021.

[73] Justin Maximilian Mittelstaedt, Jan Wacker, and Dirk Stelling. Vr aftereffect and the relation of cybersickness and cognitive performance. *Virtual Reality*, 23:143–154, 2019.

[74] B Mohler, J Campos, M Weyel, and Heinrich H Bülthoff. Gait parameters while walking in a head-mounted display virtual environment and the real world. In *13th Eurographics Symposium on Virtual Environments and 10th Immersive Projection Technology Workshop (IPT-EGVE 2007)*, pages 85–88. Eurographics Association, 2007.

[75] Jessica Isbely Montana, Cosimo Tuena, Silvia Serino, Pietro Cipresso, and Giuseppe Riva. Neurorehabilitation of spatial memory using virtual environments: a systematic review. *Journal of clinical medicine*, 8(10):1516, 2019.

[76] Marcela Cavalcanti Moreira, Anne Michelle de Amorim Lima, Karla Monica Ferraz, and Marco Aurélio Benedetti Rodrigues. Use of virtual reality in gait recovery among post stroke patients–a systematic literature review. *Disability and Rehabilitation: Assistive Technology*, 8(5):357–362, 2013.

[77] May-Britt Moser and Edvard I Moser. Distributed encoding and retrieval of spatial memory in the hippocampus. *Journal of Neuroscience*, 18(18):7535–7542, 1998.

[78] Kara Murias, Kathy Kwok, Adrian Gil Castillejo, Irene Liu, and Giuseppe Iaria. The effects of video game use on performance in a virtual navigation task. *Computers in Human Behavior*, 58:398–406, 2016.

[79] Moloud Nasiri. Gait differences in the real world and virtual reality: The effect of prior virtual reality experience. In *2021 IEEE Conference on Virtual Reality and 3D User Interfaces Abstracts and Workshops (VRW)*, pages 733–734. IEEE, 2021.

[80] Moloud Nasiri, Reza Ghaiumy Anaraky, Sabarish V Babu, and Andrew Robb. Gait differences in the real world and virtual reality: The effect of prior virtual reality experience. In *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*, pages 631–636. IEEE, 2022.

[81] Moloud Nasiri, John Porter, Kristopher Kohm, and Andrew Robb. Changes in navigation over time: A comparison of teleportation and joystick-based locomotion. *ACM Trans. Appl. Percept.*, aug 2023. Just Accepted.

[82] John O'keefe and Lynn Nadel. Précis of o'keefe & nadel's the hippocampus as a cognitive map. *Behavioral and Brain Sciences*, 2(4):487–494, 1979.

[83] Thomas D Parsons and Albert A Rizzo. Initial validation of a virtual environment for assessment of memory functioning: virtual reality cognitive performance assessment test. *CyberPsychology & Behavior*, 11(1):17–25, 2008.

[84] John Porter III, Matthew Boyer, and Andrew Robb. Guidelines on successfully porting non-immersive games to virtual reality: a case study in minecraft. In *Proceedings of the 2018 Annual Symposium on Computer-Human Interaction in Play*, pages 405–415, 2018.

[85] John Porter III and Andrew Robb. An analysis of longitudinal trends in consumer thoughts on presence and simulator sickness in vr games. In *Proceedings of the Annual Symposium on Computer-Human Interaction in Play*, pages 277–285, 2019.

[86] R Core Team. *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing, Vienna, Austria, 2017.

[87] J Wesley Regian. Virtual reality: An instructional medium for visual-spatial tasks. *Journal of communication*, 42(4):136–49, 1992.

[88] René Reinhard, Khyati Girish Shah, Corinna A Faust-Christmann, and Thomas Lachmann. Acting your avatar's age: effects of virtual reality avatar embodiment on real life walking speed. *Media Psychology*, 23(2):293–315, 2020.

[89] Anthony E Richardson, Morgan E Powers, and Lauren G Bousquet. Video game experience predicts virtual, but not real navigation performance. *Computers in Human Behavior*, 27(1):552–560, 2011.

[90] Bernhard E Riecke, Jörg Schulte-Pelkum, Marios N Avraamides, Markus Von Der Heyde, and Heinrich H Bülthoff. Scene consistency and spatial presence increase the sensation of self-motion in virtual reality. In *Proceedings of the 2nd Symposium on Applied Perception in Graphics and Visualization*, pages 111–118, 2005.

[91] Andrew Robb, Kristopher Kohm, and John Porter. Experience matters: Longitudinal changes in sensitivity to rotational gains in virtual reality. *ACM Transactions on Applied Perception*, 19(4):1–18, 2022.

[92] Roy A Ruddle and Simon Lessels. The benefits of using a walking interface to navigate virtual environments. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 16(1):1–18, 2009.

[93] Franklin E Satterthwaite. An approximate distribution of estimates of variance components. *Biometrics bulletin*, 2(6):110–114, 1946.

[94] Thomas Schubert, Frank Friedmann, and Holger Regenbrecht. The experience of presence: Factor analytic insights. *Presence: Teleoperators & Virtual Environments*, 10(3):266–281, 2001.

[95] Gideon Schwarz. Estimating the dimension of a model. *The annals of statistics*, pages 461–464, 1978.

[96] Angelia Sebok, Espen Nystad, and Stein Helgar. Navigation in desktop virtual environments: an evaluation and recommendations for supporting usability. *Virtual Reality*, 8(1):26–40, 2004.

[97] Abhishek Seth, Judy M Vance, and James H Oliver. Virtual reality for assembly methods prototyping: a review. *Virtual reality*, 15:5–20, 2011.

[98] Amir Mehdi Shayan, Arman Khazaei, Amin Hamed, Arsalan Amralizadeh, and Mehdi Tale Masouleh. Shrewdshoe, a smart pressure sensitive wearable platform. In *2018 6th RSI International Conference on Robotics and Mechatronics (IcRoM)*, pages 458–463. IEEE, 2018.

[99] Thomas B Sheridan et al. Musings on telepresence and virtual presence. *Presence Teleoperators Virtual Environ.*, 1(1):120–125, 1992.

[100] Mel Slater. Immersion and the illusion of presence in virtual reality. *British journal of psychology*, 109(3):431–433, 2018.

[101] Mel Slater, Anthony Steed, John McCarthy, and Francesco Maringelli. The influence of body movement on subjective presence in virtual environments. *Human factors*, 40(3):469–477, 1998.

[102] Mel Slater, Martin Usoh, and Anthony Steed. Taking steps: the influence of a walking technique on presence in virtual reality. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 2(3):201–219, 1995.

[103] Shamus P Smith and Sam Du'Mont. Measuring the effect of gaming experience on virtual environment navigation tasks. In *2009 IEEE symposium on 3D user interfaces*, pages 3–10. IEEE, 2009.

[104] José L Soler-Domínguez, Carla de Juan, Manuel Contero, and Mariano Alcañiz. I walk, therefore i am: A multidimensional study on the influence of the locomotion method upon presence in virtual reality. *Journal of Computational Design and Engineering*, 7(5):577–590, 2020.

[105] Kay M Stanney, Kelly S Hale, Isabelina Nahmens, and Robert S Kennedy. What to expect from immersive virtual environment exposure: Influences of gender, body mass index, and past experience. *Human factors*, 45(3):504–520, 2003.

[106] Kay M Stanney, Kelly S Kingdon, David Graeber, and Robert S Kennedy. Human performance in immersive virtual environments: Effects of exposure duration, user control, and scene complexity. *Human performance*, 15(4):339–366, 2002.

[107] Qi Sun, Li-Yi Wei, and Arie Kaufman. Mapping virtual and physical reality. *ACM Transactions on Graphics (TOG)*, 35(4):1–12, 2016.

[108] Ancrêt Szpak, Stefan Carlo Michalski, Dimitrios Saredakis, Celia S. Chen, and Tobias Loetscher. Beyond feeling sick: The visual and cognitive aftereffects of virtual reality. *IEEE Access*, 7:130883–130892, 2019.

[109] Ron Tamborini and Paul Skalski. The role of presence in the experience of electronic games. In *Playing video games*, pages 263–281. Routledge, 2012.

[110] David Trenholme and Shamus P Smith. Computer game engines for developing first-person virtual environments. *Virtual reality*, 12(3):181–187, 2008.

[111] Unity. Dungeon architect: Utilities tools.

[112] Martin Usoh, Kevin Arthur, Mary C Whitton, Rui Bastos, Anthony Steed, Mel Slater, and Frederick P Brooks Jr. Walking¿ walking-in-place¿ flying, in virtual environments. In *Proceedings of the 26th annual conference on Computer graphics and interactive techniques*, pages 359–364, 1999.

[113] Sina Varmaghani, Zahra Abbasi, Séamas Weech, and Javad Rasti. Spatial and attentional aftereffects of virtual reality and relations to cybersickness. *Virtual Reality*, 26(2):659–668, 2022.

[114] Sara Vlahović, Mirko Suznjevic, and Lea Skorin-Kapov. Subjective assessment of different locomotion techniques in virtual reality environments. In *2018 Tenth International Conference on Quality of Multimedia Experience (QoMEX)*, pages 1–3. IEEE, 2018.

[115] Cesko C Voeten. Using 'buildmer'to automatically find & compare maximal (mixed) models, 2020.

[116] David Waller and Adam R Richardson. Correcting distance estimates by interacting with immersive virtual environments: effects of task and available sensory information. *Journal of Experimental Psychology: Applied*, 14(1):61, 2008.

[117] Tim Weißker, André Kunert, Bernd Fröhlich, and Alexander Kulik. Spatial updating and simulator sickness during steering and jumping in immersive virtual environments. In *2018 IEEE Conference on Virtual Reality and 3D User Interfaces (VR)*, pages 97–104. IEEE, 2018.

[118] Jeremy D Wendt, Mary C Whitton, and Frederick P Brooks. Gud wip: Gait-understanding-driven walking-in-place. In *2010 IEEE Virtual Reality Conference (VR)*, pages 51–58. IEEE, 2010.

[119] Hadley Wickham. *ggplot2: Elegant Graphics for Data Analysis*. Springer-Verlag New York, 2009.

[120] Preston Tunnell Wilson, William Kalescky, Ansel MacLaughlin, and Betsy Williams. Vr locomotion: walking¿ walking in place¿ arm swinging. In *Proceedings of the 15th ACM SIGGRAPH Conference on Virtual-Reality Continuum and Its Applications in Industry-Volume 1*, pages 243–249, 2016.

[121] Mengxin Xu, María Murcia-López, and Anthony Steed. Object location memory error in virtual and real environments. In *2017 IEEE Virtual Reality (VR)*, pages 315–316. IEEE, 2017.

[122] Feng Yang and George A King. Dynamic gait stability of treadmill versus overground walking in young adults. *Journal of Electromyography and Kinesiology*, 31:81–87, 2016.

[123] Yulong Zhang, Zhuangsheng Zhu, and Shibo Wang. Method Based on the Characteristics of Gait. *2018 Ubiquitous Positioning, Indoor Navigation and Location-Based Services (UPINLBS)*, pages 1–5, 2018.